Radioactively Powered Emission from Neutron Star Mergers

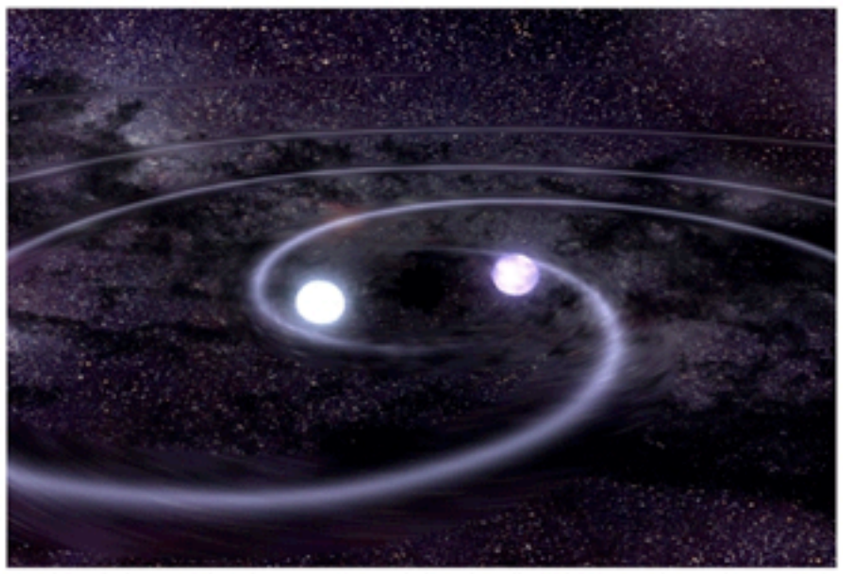
Masaomi Tanaka (NAOJ)

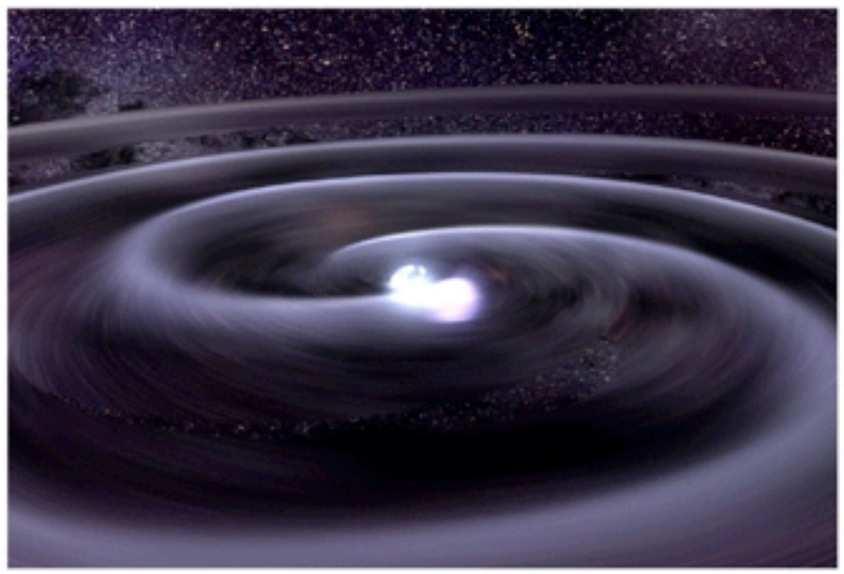
- MT & Hotokezaka 2013, ApJ, 775, 113
- MT, Hotokezaka, Kyutoku, Wanajo, Kiuchi, Sekiguchi, Shibata 2014, ApJ, 780, 31
- Hotokezaka, Kyutoku, MT, Kiuchi, Sekiguchi, Shibata, Wanajo 2013, ApJ, 778, L16

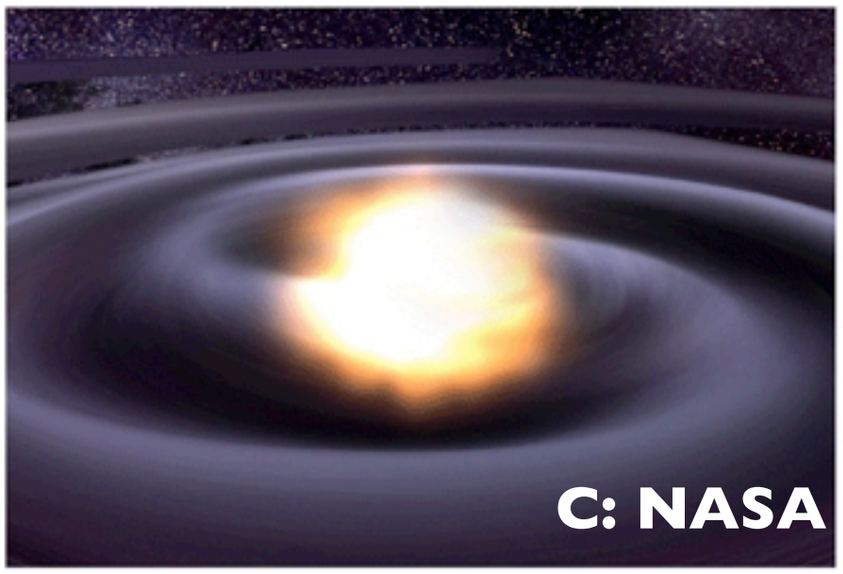
New astronomy with gravitational waves

2017 -
- Advanced LIGO (US)
- Advanced Virgo (Europe)
- KAGRA (Japan)

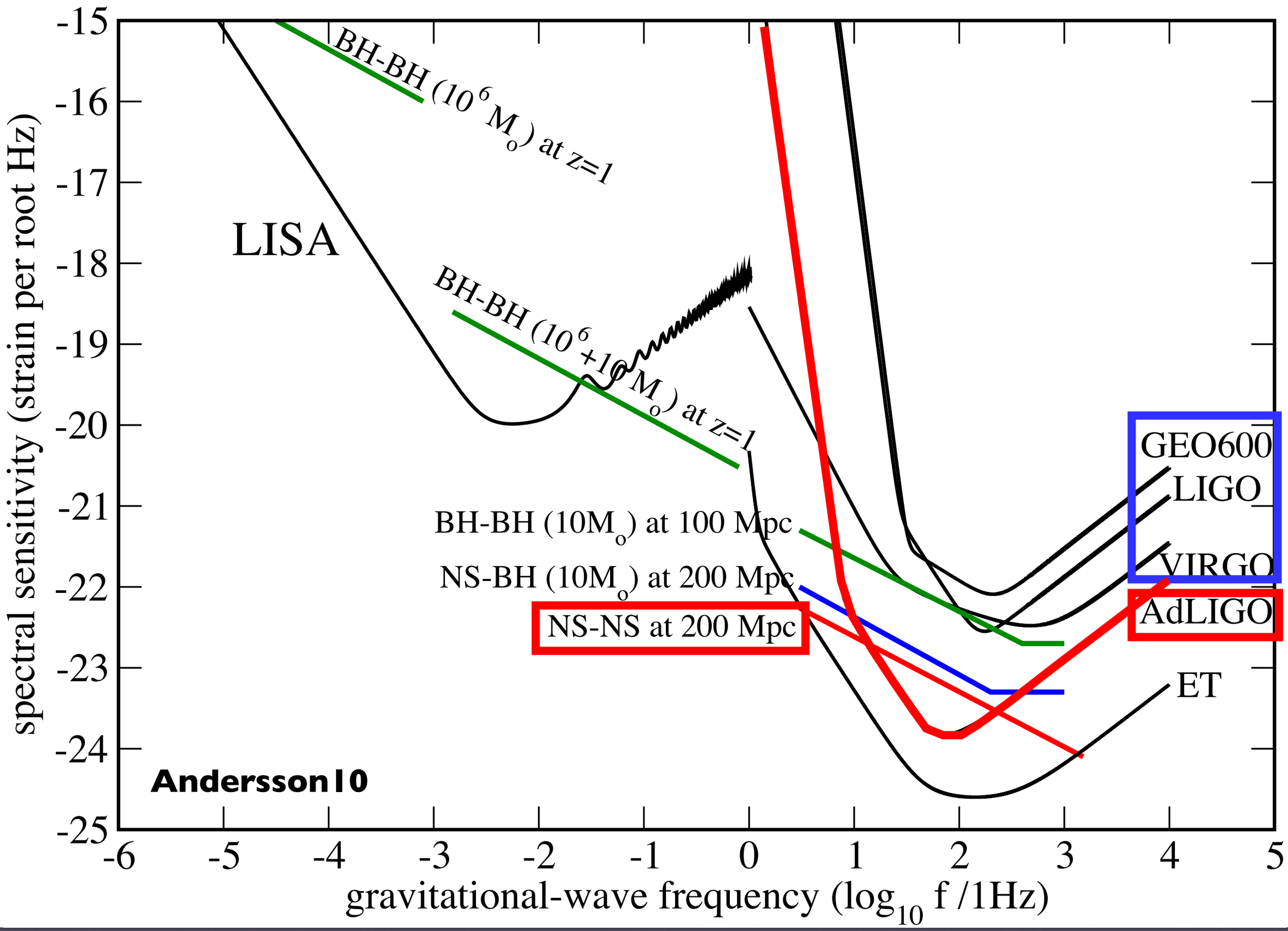
NS-NS merger with 200 Mpc
~ 30 events/yr
(~0.3-300)







C: NASA


spectral sensitivity (strain per root Hz)
gravitational-wave frequency ($\log_{10}$ f /1Hz)
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
LISA
BH-BH ($10^6 M_o$) at z=1
BH-BH (10^6+$10^6 M_o$) at z=1
BH-BH ($10M_o$) at 100 Mpc
NS-BH ($10M_o$) at 200 Mpc
NS-NS at 200 Mpc
GEO600
LIGO
VIRGO
AdLIGO
ET
Andersson10

2 deg

Kiso 1m
Schmidt telescope

~ 200 galaxies / 4deg^2
(< 200 Mpc)

GW alert error box

e.g. 10 deg x 10 deg

~ 5000 galaxies

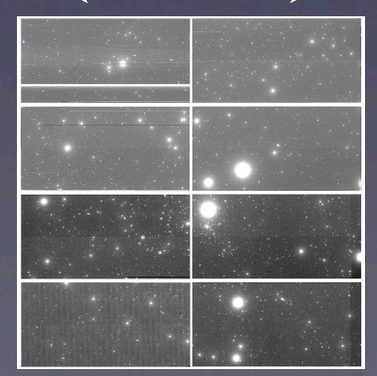
(< 200 Mpc)

No electromagnetic counterpart
No gravitational wave astronomy

Distance to GW sources
- Intrinsic GW amplitude

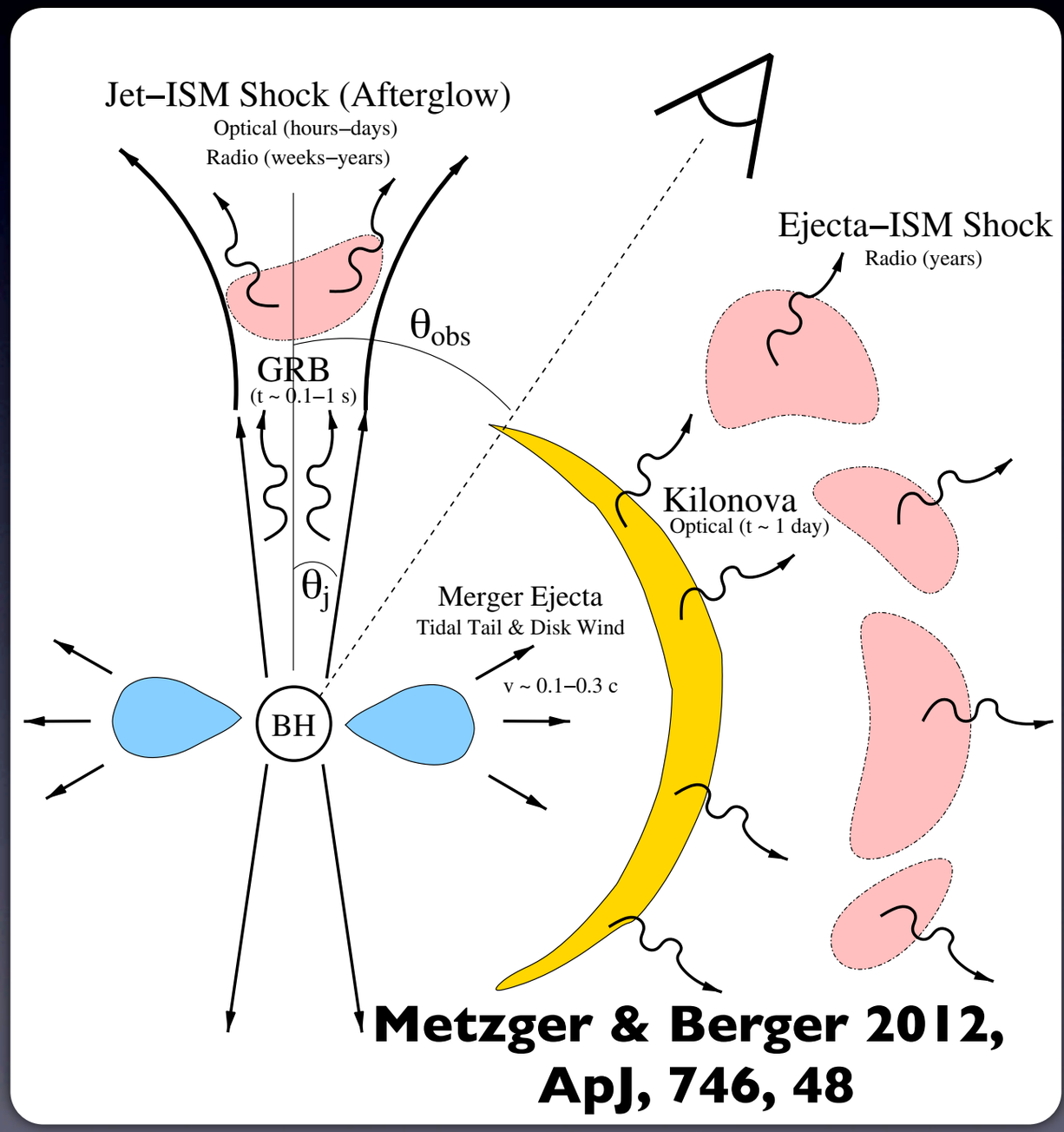
Nature of GW sources
- Progenitor system

2 deg

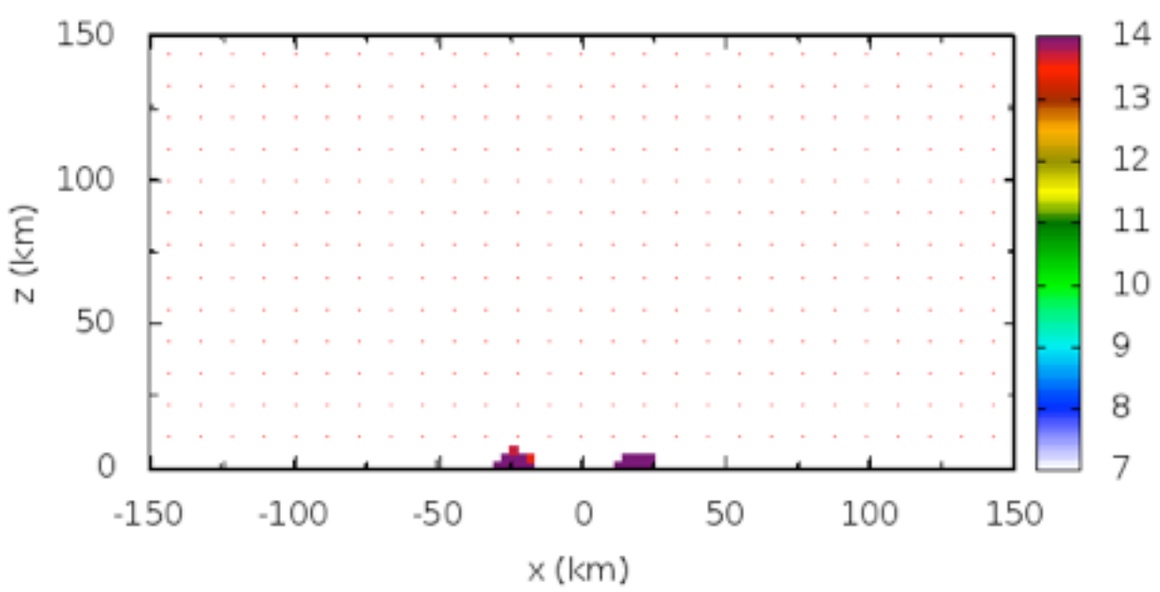


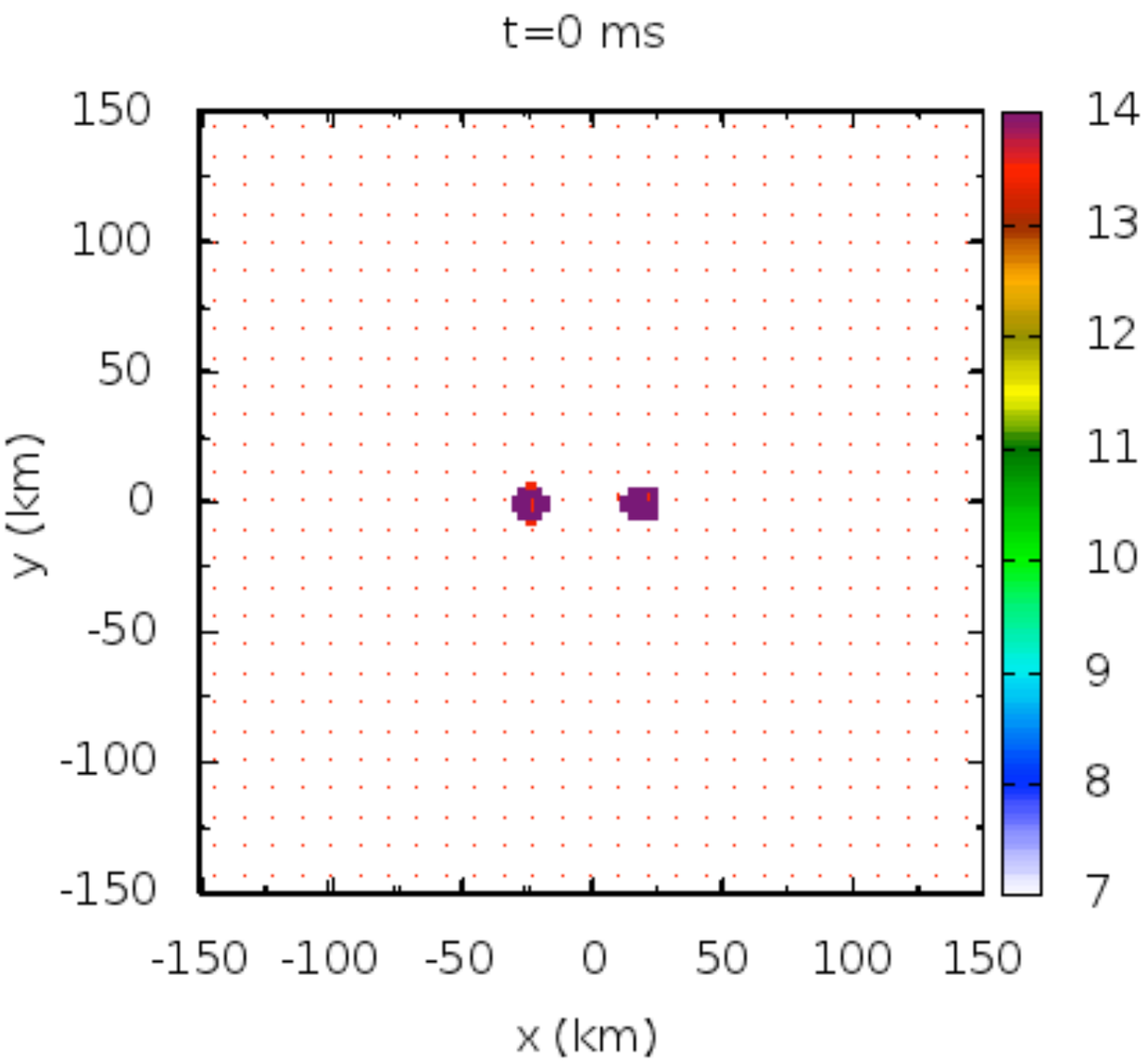
EM emission from NS-NS merger = EM counterparts of GW sources

- On-axis short GRB
- Off-axis radio/optical afterglow
- **Radioactive emission (r-process nuclei) => optical/NIR kilonova/macronova**



Metzger & Berger 2012, ApJ, 746, 48

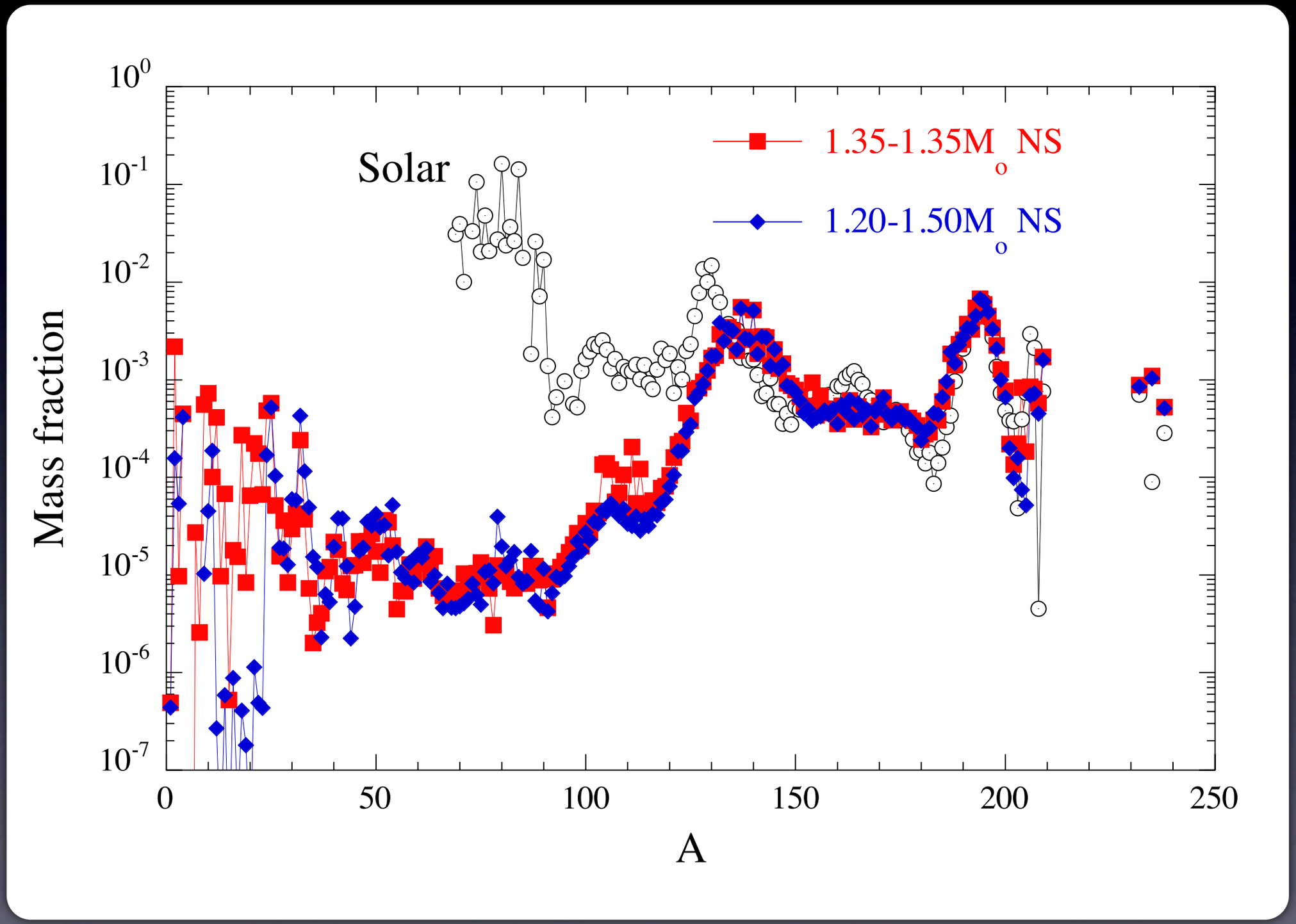




Mass ejection from NS mergers

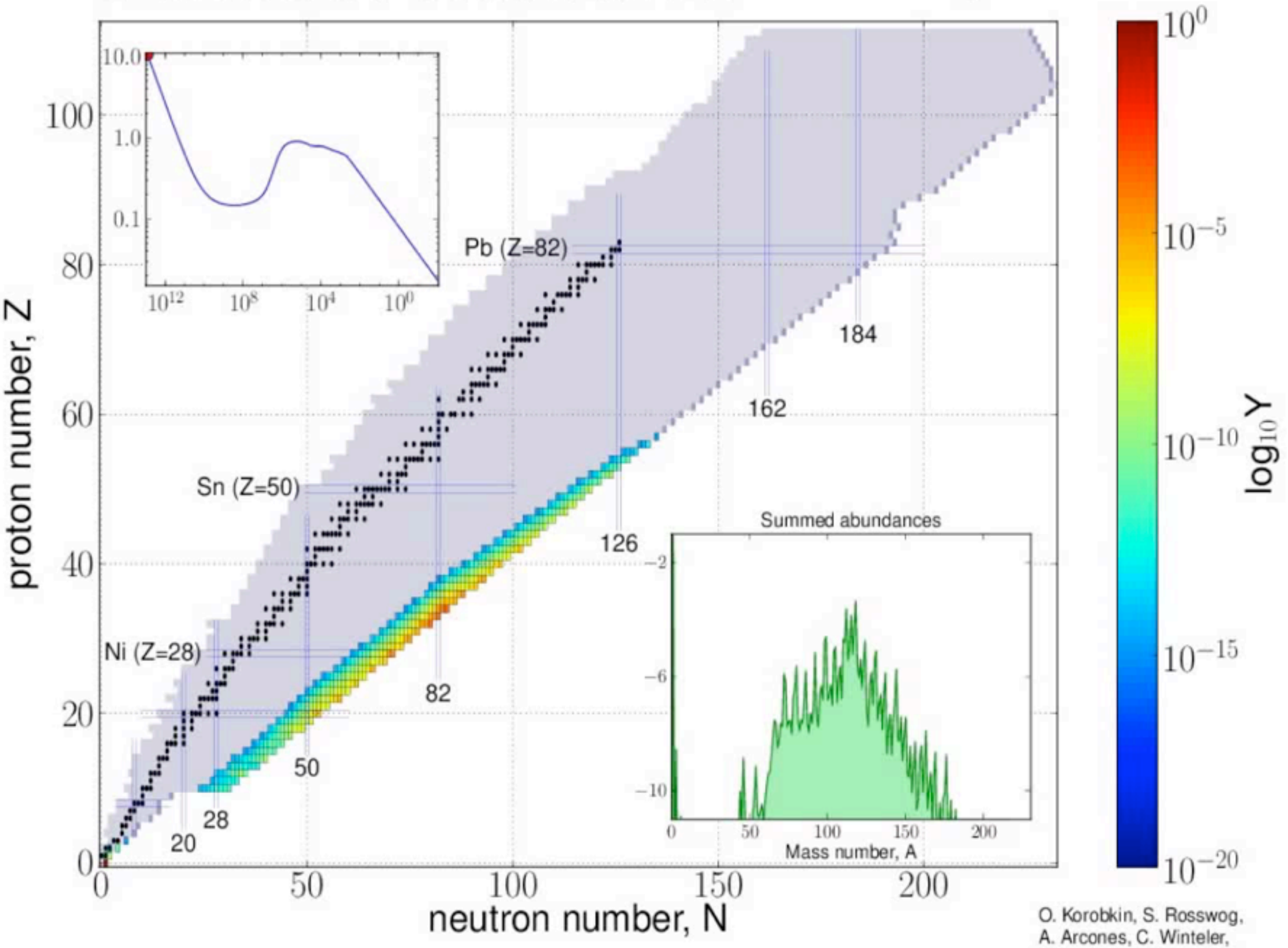
Hotokezaka+13

r-process nucleosynthesis



Goriely+11

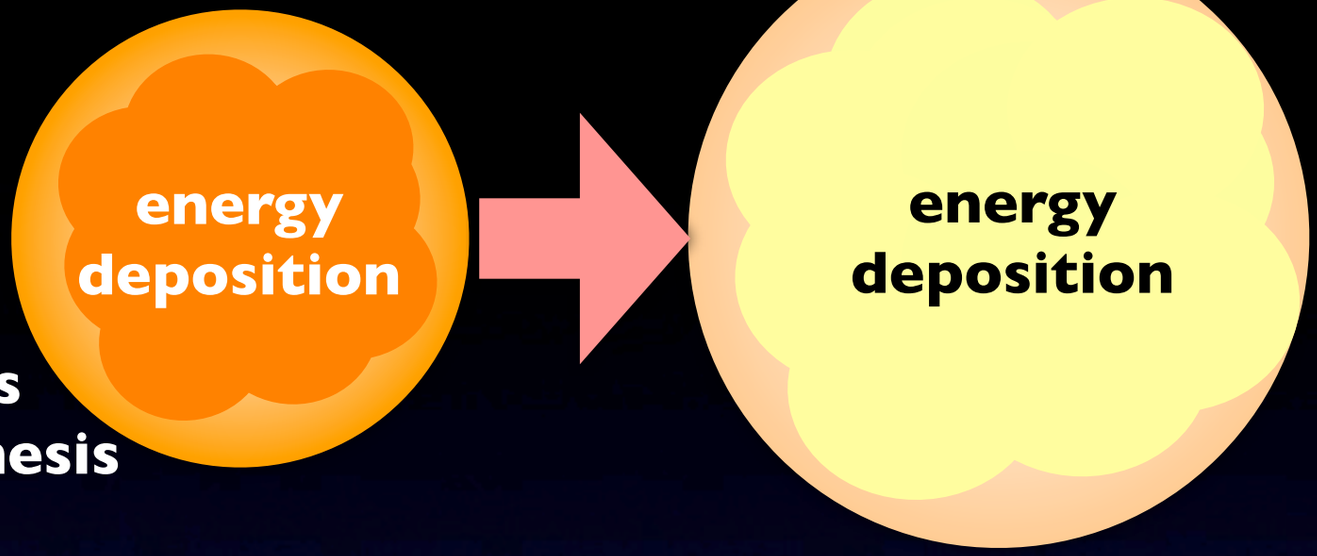
t : 0.00e+00 s / T : 10.96 GK / ρ_b : 8.71e+12 g/cm^3



O. Korobkin, S. Rosswog,
A. Arcones, C. Winteler,
arXiv:1206.2379

Expected emission

Li & Paczynski 98
Kulkarni 05
Metzger+10



r-process nucleosynthesis

Timescale

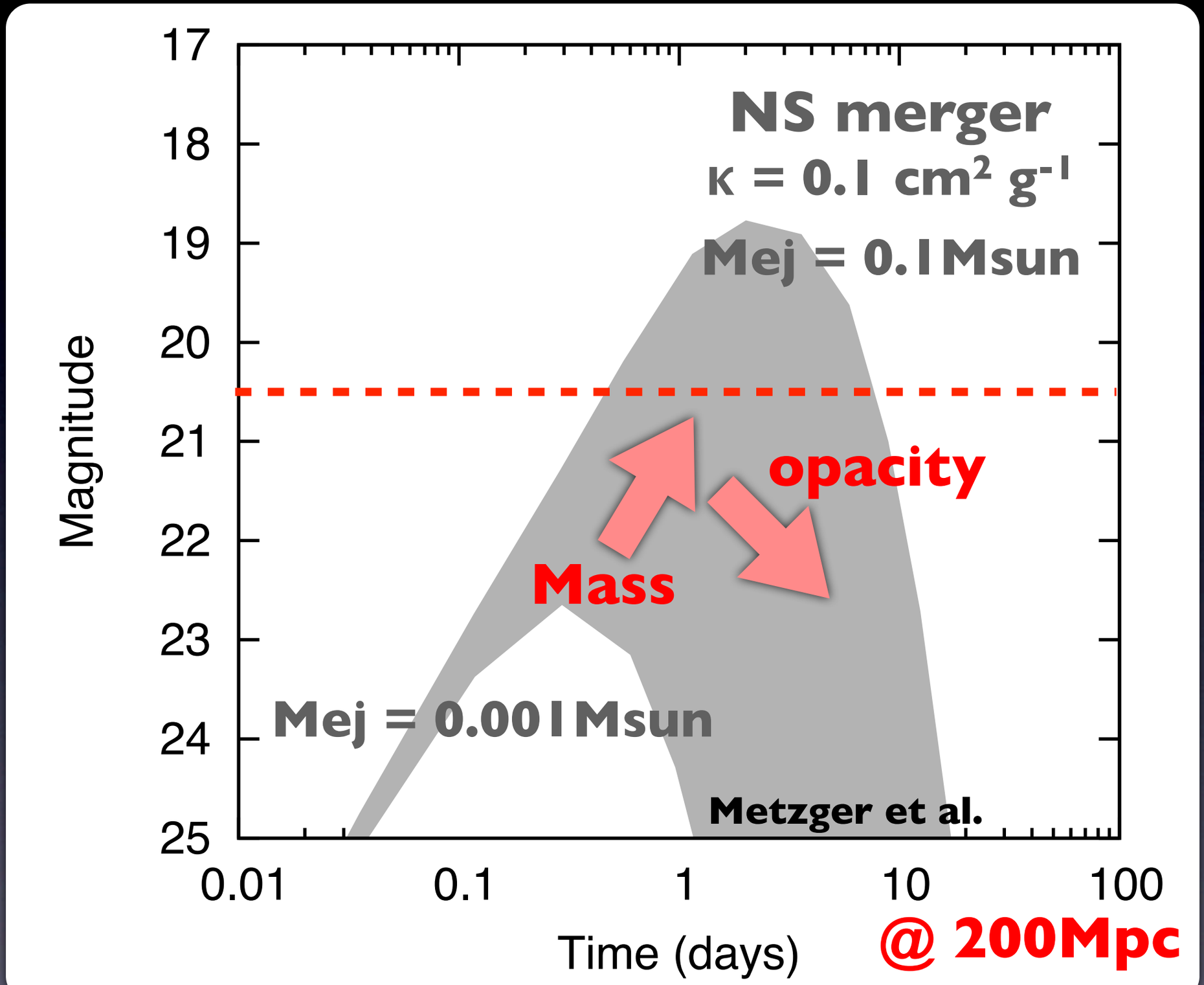
$$t_p \sim 1 \text{ day} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}$$

Luminosity

$$L \sim 10^{42} \text{ erg s}^{-1} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}}\right)^{-1/2}$$

~ 20 mag at 200 Mpc
(1m-class telescopes)

bound-bound opacity of Fe


NS merger
κ = 0.1 cm² g⁻¹
Mej = 0.1Msun
opacity
Mass
Mej = 0.001Msun
Metzger et al.
Magnitude
17
18
19
20
21
22
23
24
25
0.01
0.1
1
10
100
Time (days)
@ 200Mpc

KISS: KIso Supernova Survey

2012 Apr: Dry run -
2012 Sep: Main survey -

- Extremely high cadence
  - 1-hr cadence <= 2-3 days
  - 4 deg^2 FOV (KWFC, Sako et al.)
  - ~ 21 mag in g-band (3 min)
  - ~50-100 deg^2 /day
- High SFR field (< 200 Mpc, 30-100 Msun/yr)
- ~100 nights/yr (around new moon)

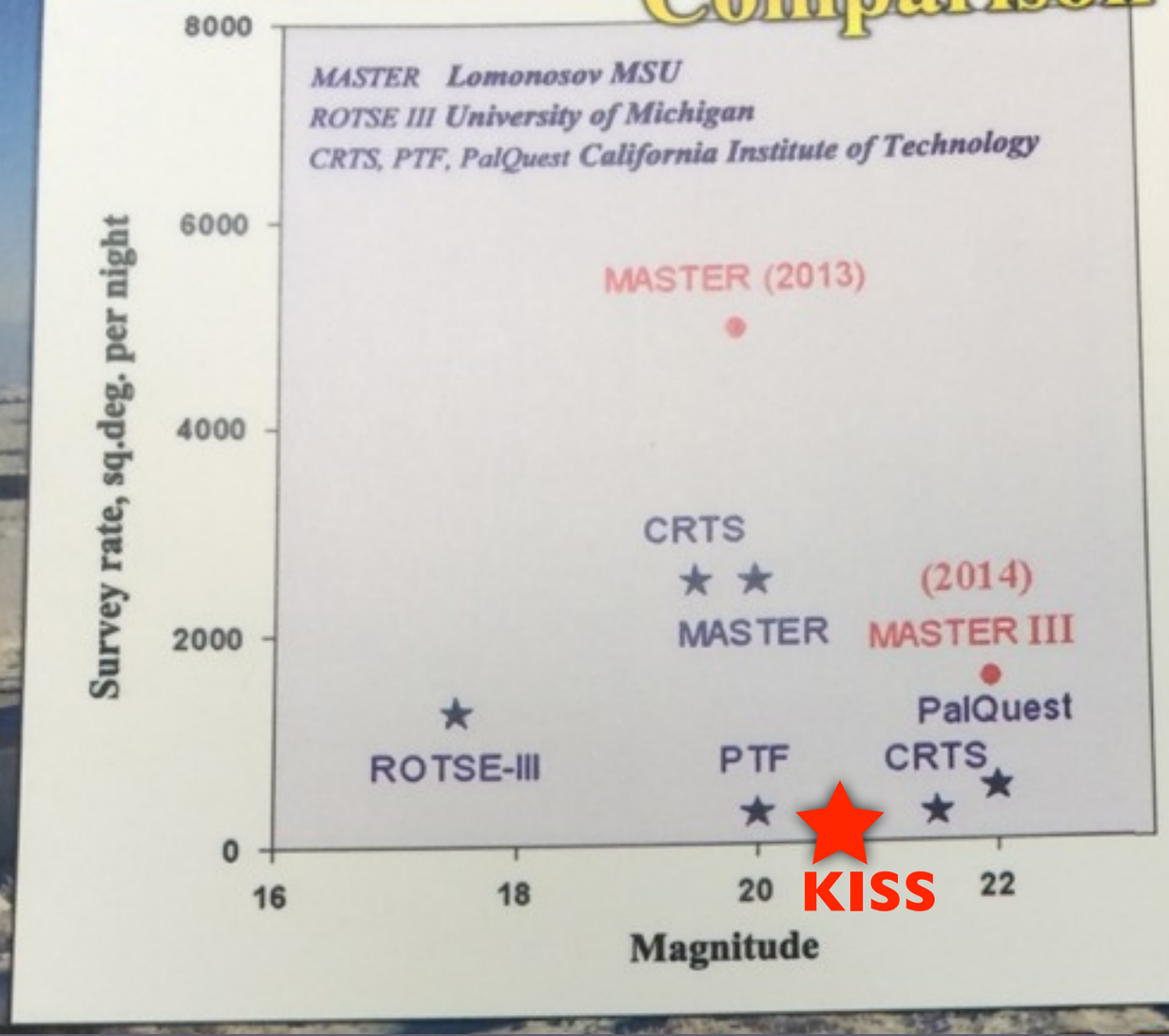
Goal: Detection of SN shock breakout

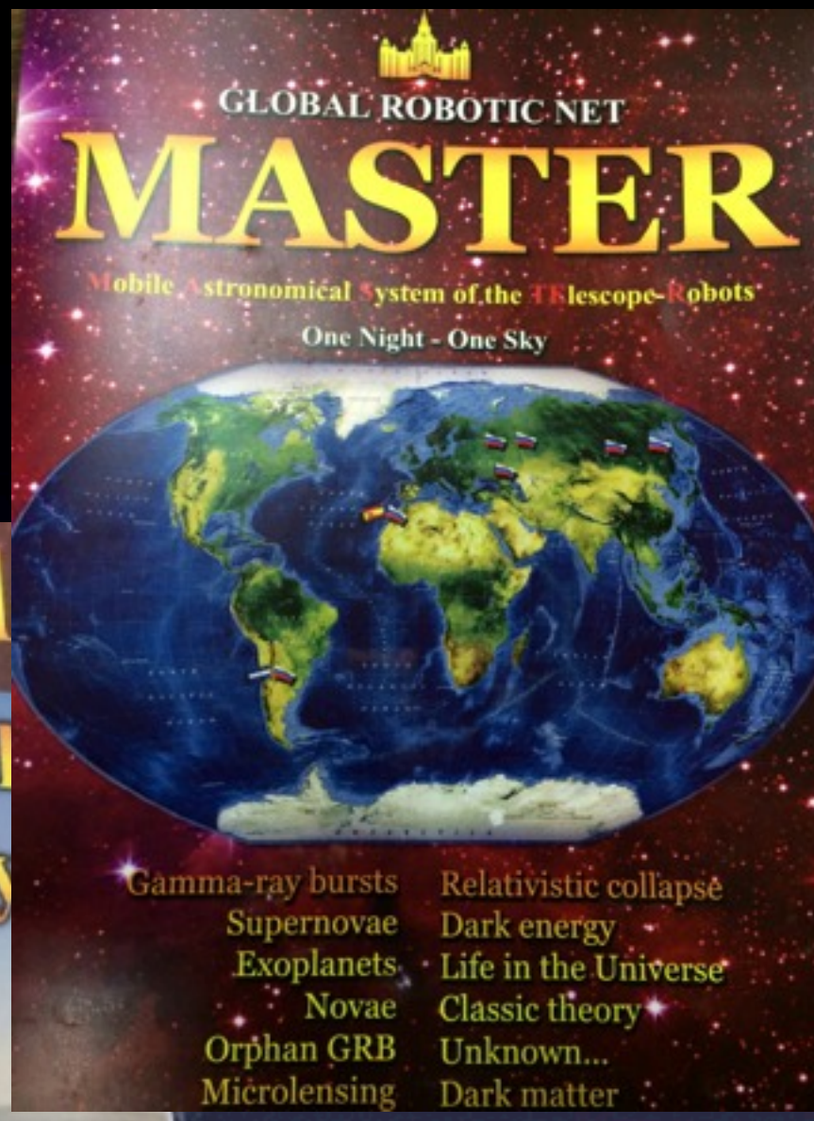
KISS collaboration

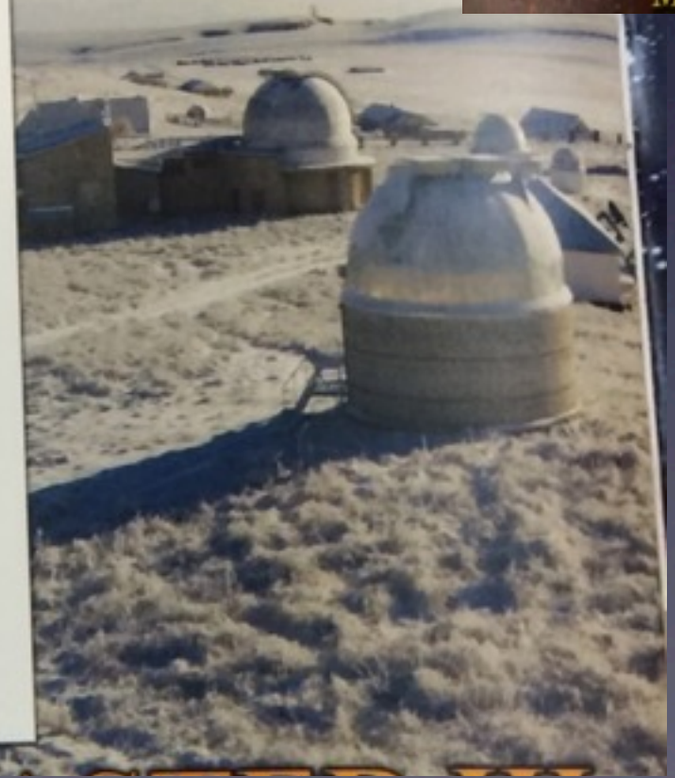
- **Survey members**
  - **Tomoki Morokuma (PI), Nozomu Tominaga, Masaomi Tanaka, Emiko Matsumoto,** Kensho Mori, Koji Kawabata (and Hiroshima group), Yoshihiko Saito (and Tokyo Tech group), Nobuharu Ukita, Michael Richmond, Yuji Urata
- **Indian Institute of Astrophysics**
  - Devendra Sahu
- **Carnegie Supernova Project (CSP)**
  - Eric Hsiao, Maximilian Stritzinger, Mark Phillips, Nidia Morrell, Carlos Contreras, Francesco Taddia
- **Telescopio Nazionale Galileo (TNG)**
  - Paolo Mazzali, Emma Walker, Elena Pian
- **SNFactory**
  - Greg Aldering
- **Sternberg Astronomical Institute**
  - Dmitry Tsvetkov, Nikolay Pvalyuk

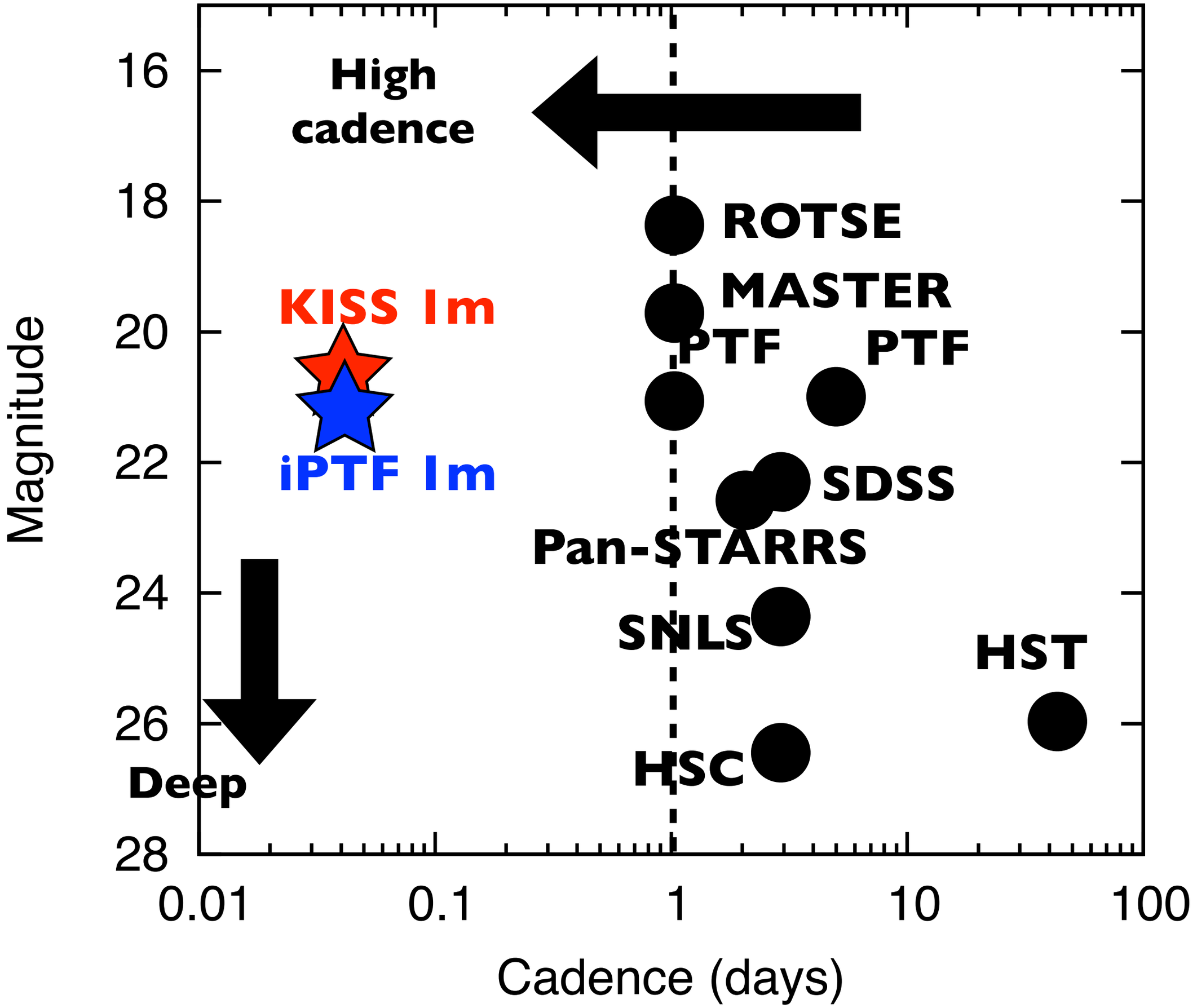
MASTER in the Worl

Comparison of the Worl Sky Survey

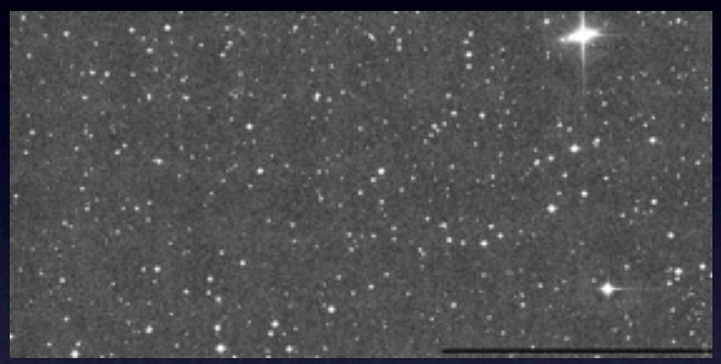




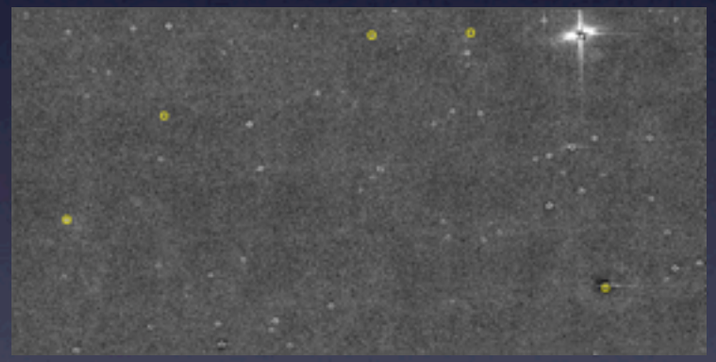



High cadence
Deep
KISS Im
iPTF Im
ROTSE
MASTER
PTF
PTF
SDSS
Pan-$TARRS
SNLS
HST
HSC
16
18
20
22
24
26
28
Magnitude
0.01
0.1
1
10
100
Cadence (days)

Kiso observatory



Standard pipeline



Transient pipeline

< 10 min

~ 50GB/day

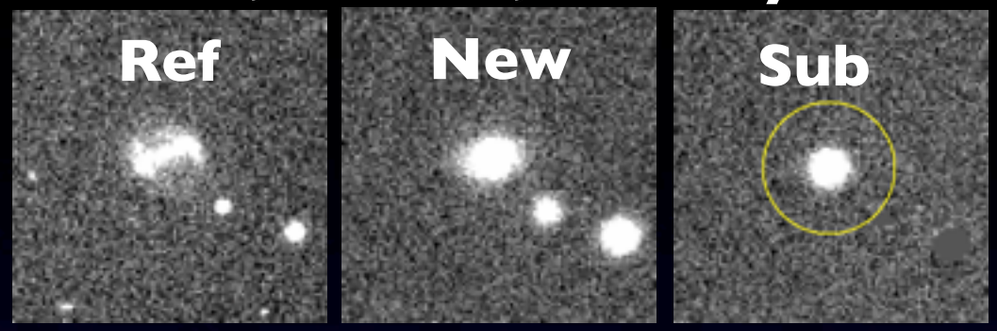
cut-out images (~1,000-10,000 /day)

KISS database

source info

Anywhere

cut-out images
1,000 - 10,000 /day



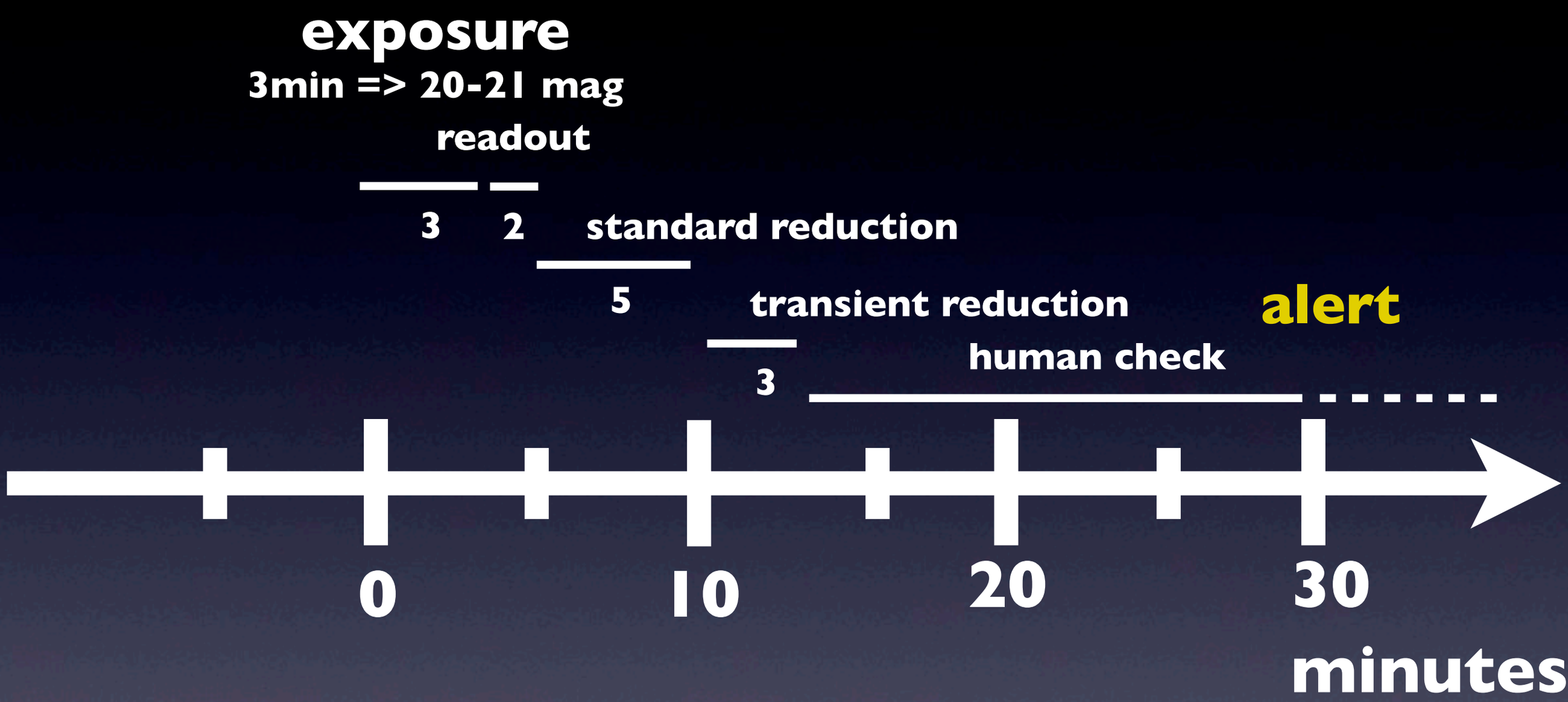
KISS database

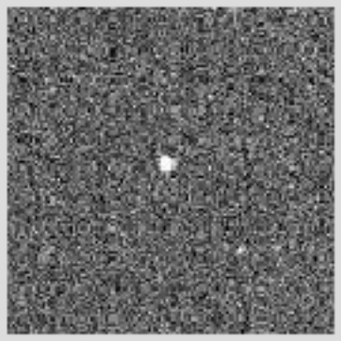
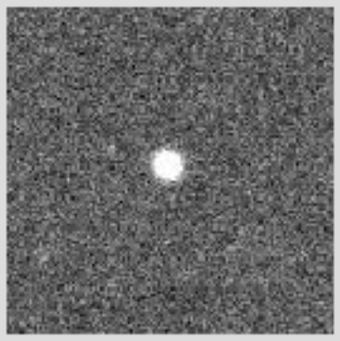
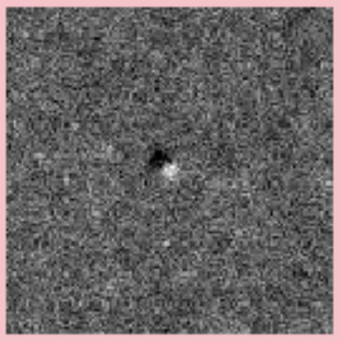
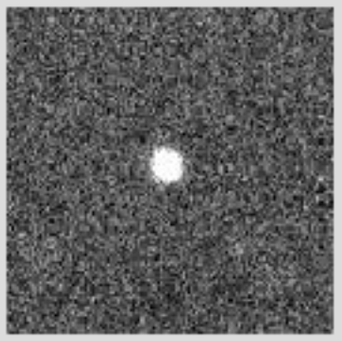
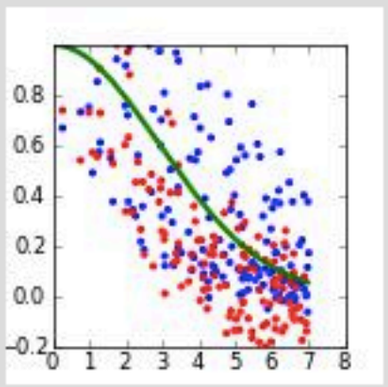
source info

KISS interface

~ 20 amateur astronomers

Timeline


exposure
3min => 20-21 mag
readout
3
2
standard reduction
5
transient reduction
3
human check
alert
0
10
20
30
minutes

No	Request	FitsID	Reference	New	Subtracted	Previous	Profile
			(2' x 2')	(2' x 2')	(2' x 2')	(2' x 2')	7pix
1	source ID **1040730** submit	KSFJ1209+1700 0062320_0					new sub 
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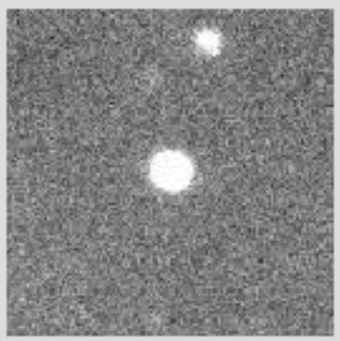
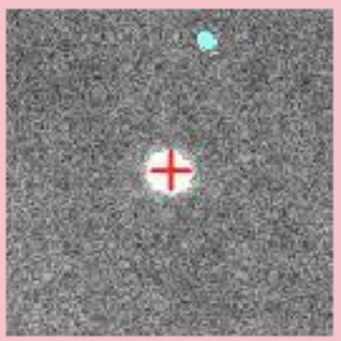
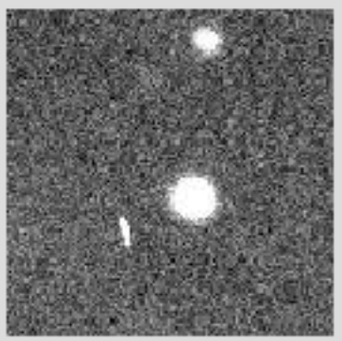
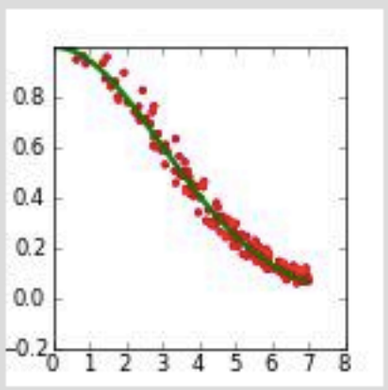
2	source ID **1040731** submit	KSFJ1209+1700 0062320_1					new sub 
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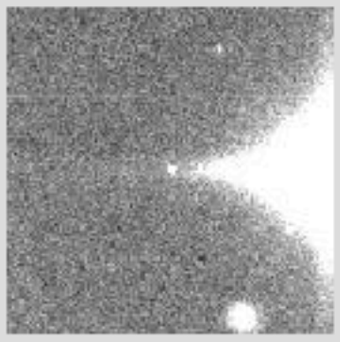
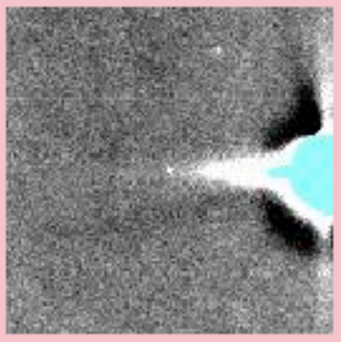
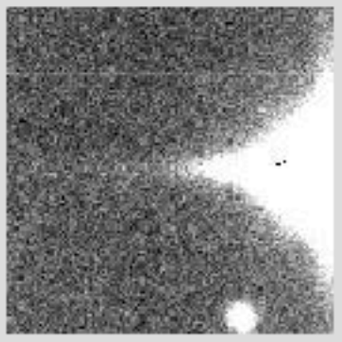
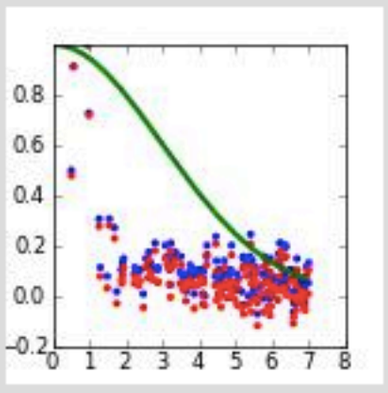
3	source ID **1040732** submit	KSFJ1209+1700 0062320_1					new sub 
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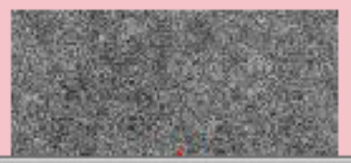
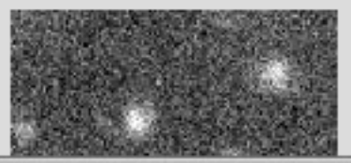
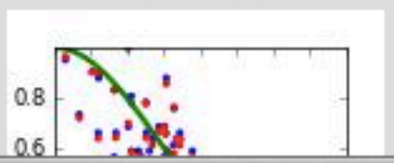
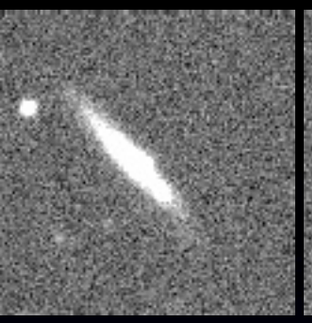
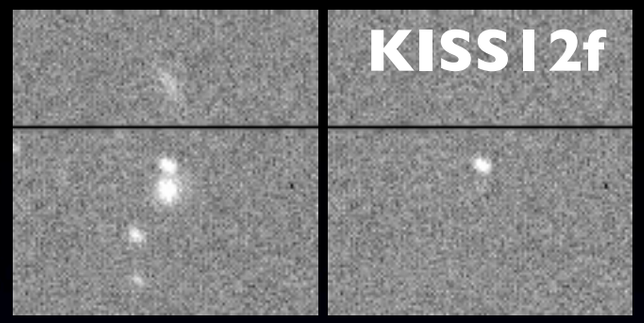
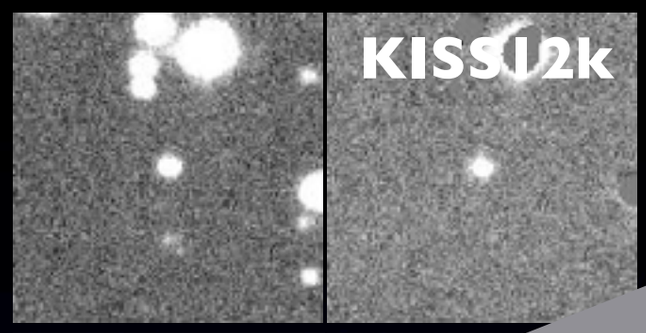
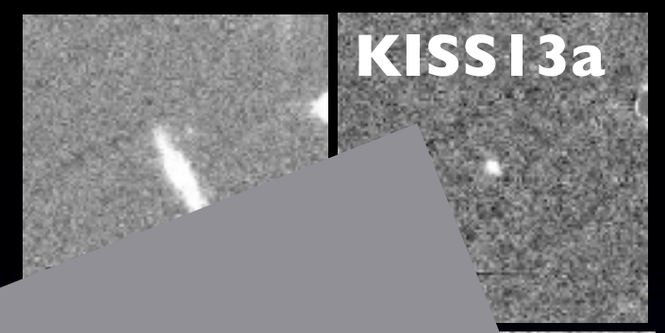
	source ID **1040733** submit	KSFJ1209+1700 0062320_1					new sub 

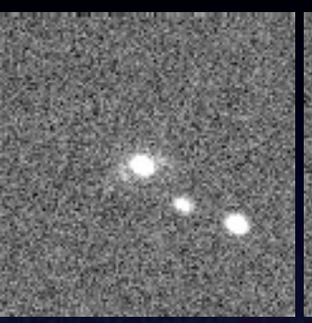
65 SN candidates (as of 2014 Feb)

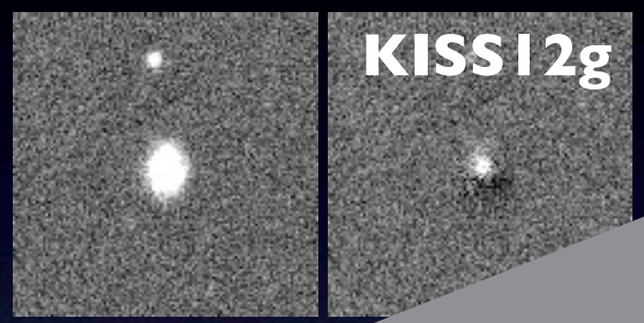


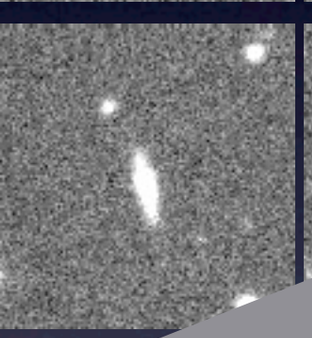


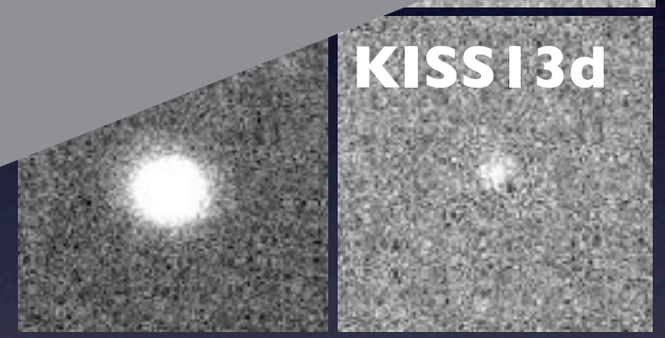


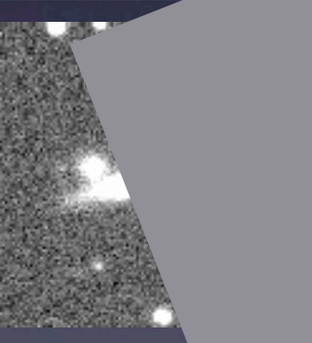


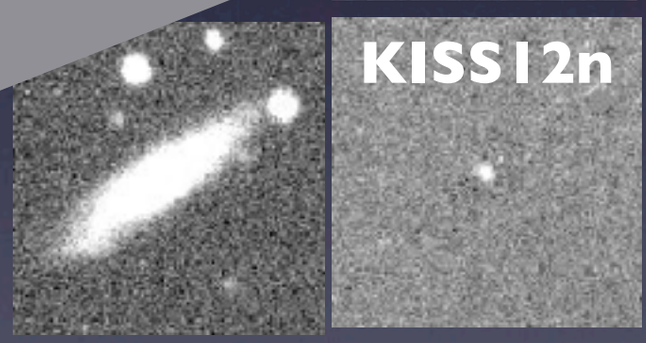


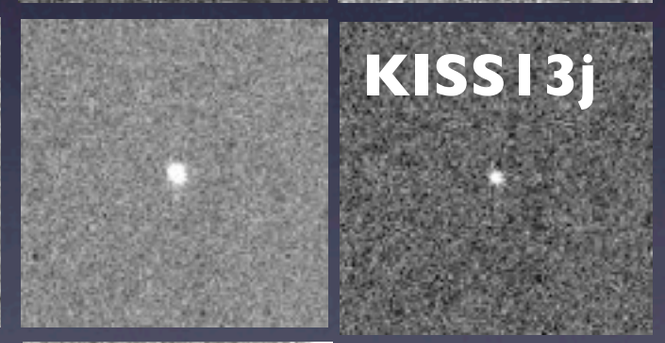


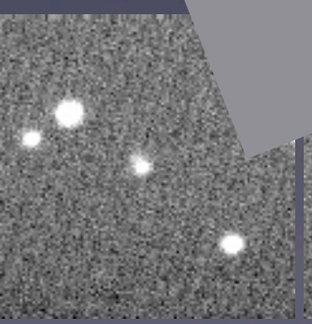


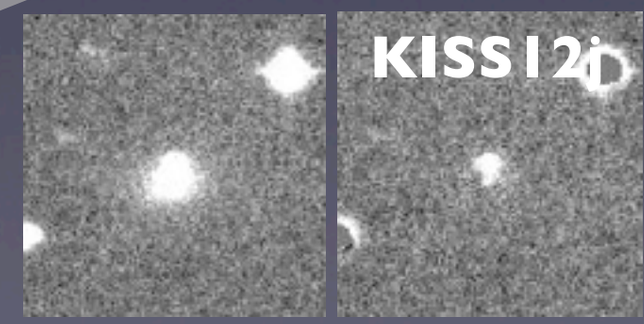


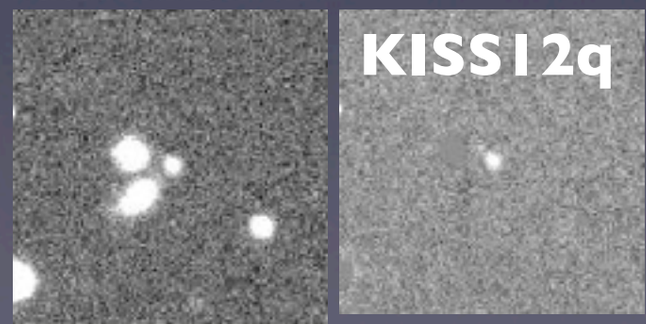


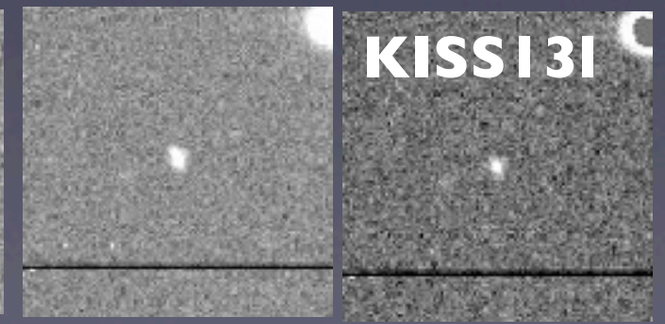




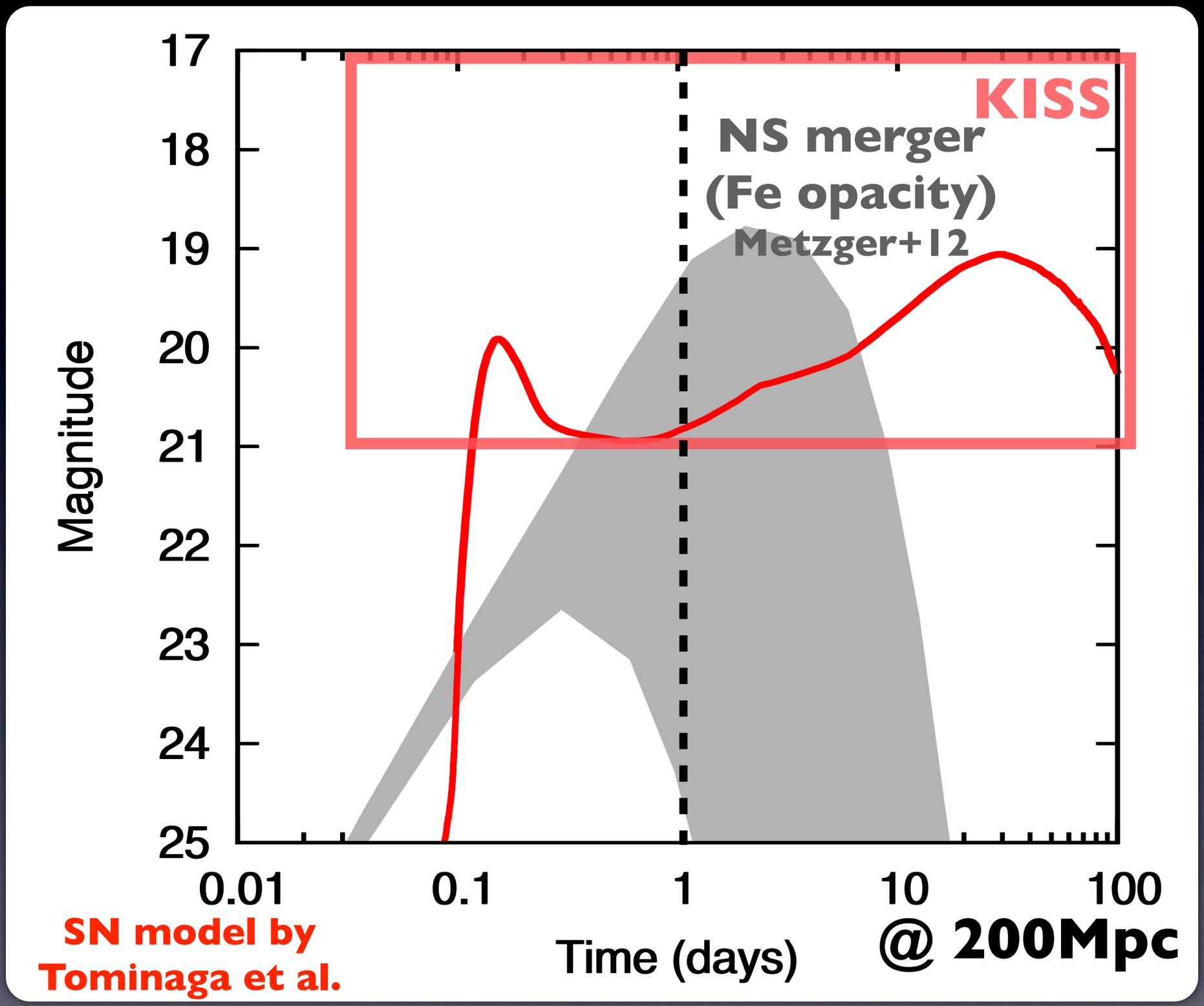






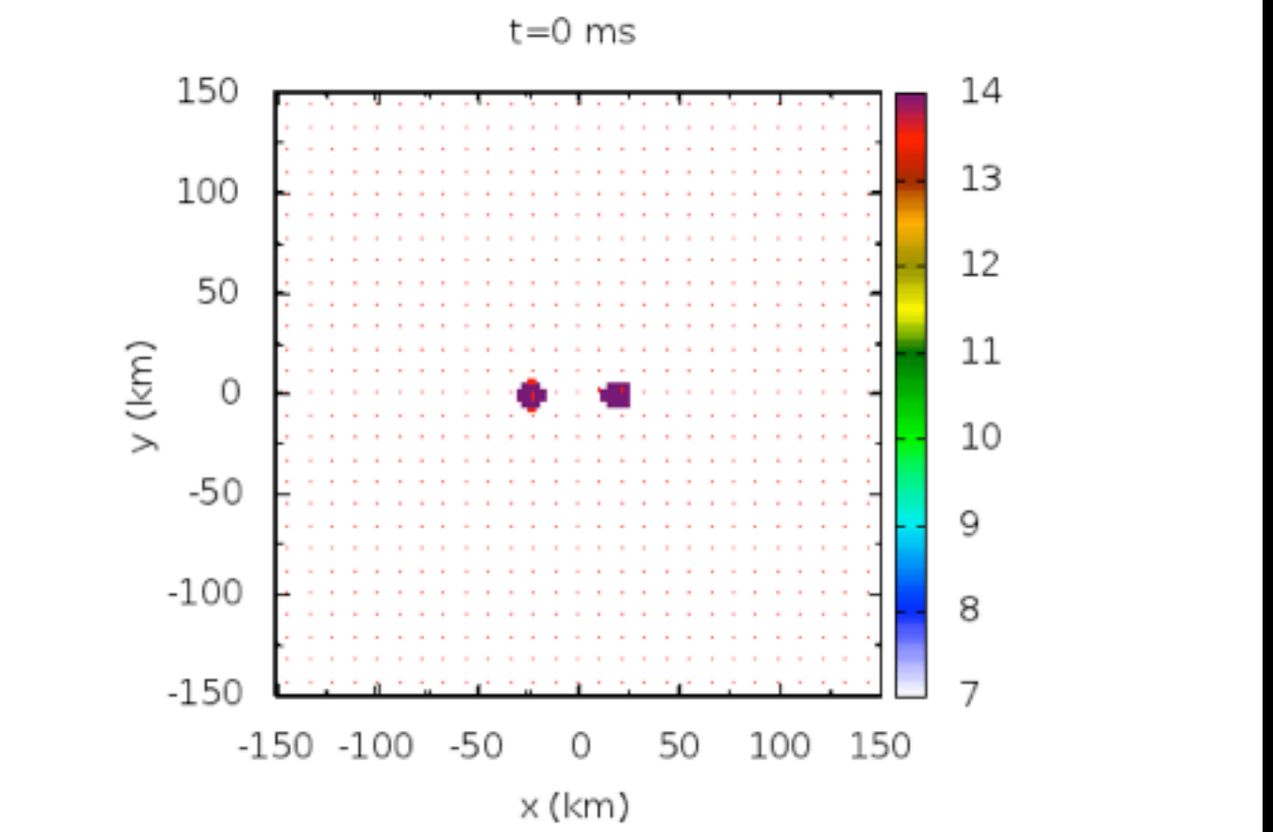


No shock breakout yet...
stay tuned!

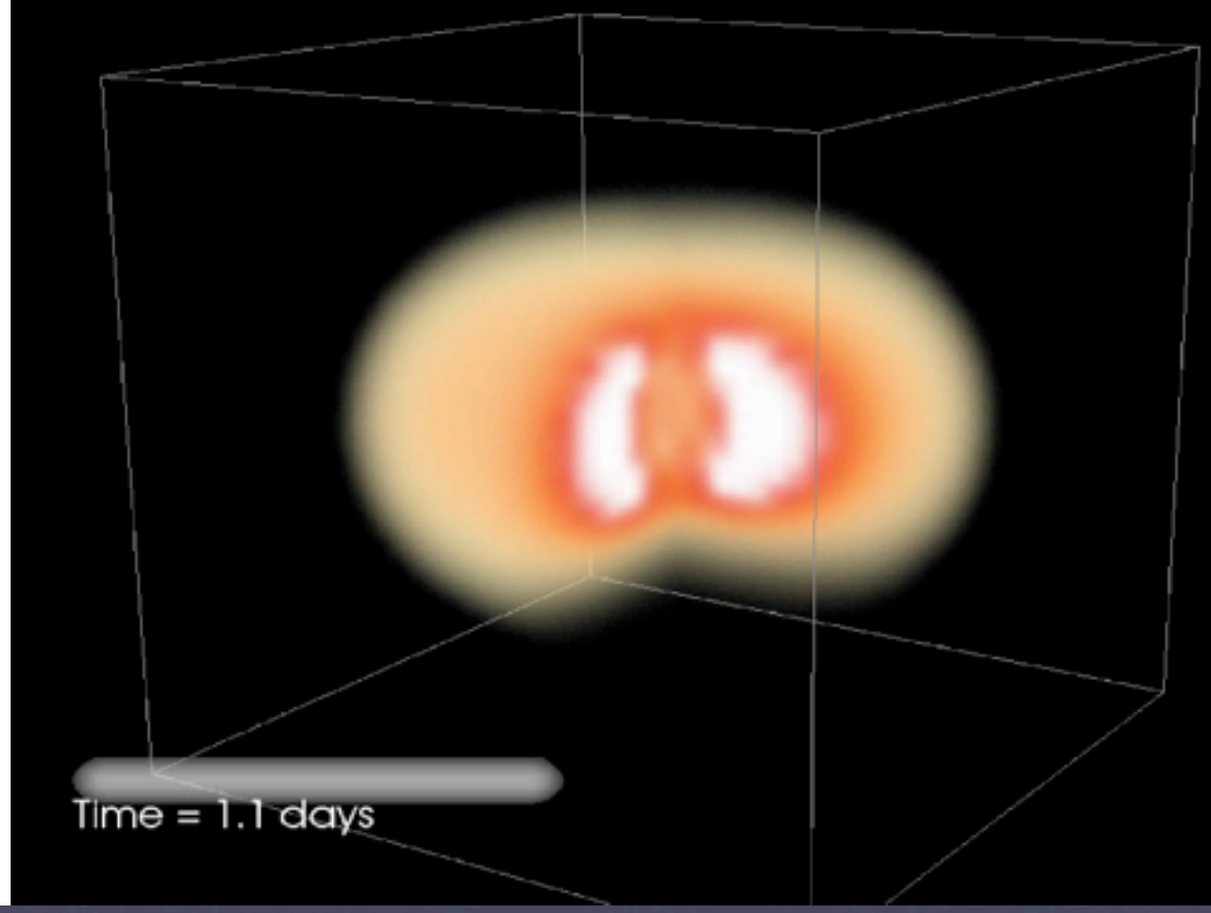

KISS
NS merger
(Fe opacity)
Metzger+12
Magnitude
17
18
19
20
21
22
23
24
25
0.01
0.1
1
10
100
Time (days)
@ 200Mpc
SN model by
Tominaga et al.

Numerical relativity

3D, time-dependent, multi-frequency radiative transfer



Hotokezaka et al. 2013



MT & Hotokezaka 2013

1. Opacity of NS merger ejecta?
2. Characteristic feature of NS merger?

3D Monte Carlo radiation transfer code

- Cartesian 3D grid (in velocity) 32^3
- Frequency 100-25,000 A with $d\lambda = 10A$ (~2500 mesh points)
- No hydrodynamics
- b-b (w/ expansion), b-f, f-f, e-scat opacity
- Local thermodynamic equilibrium
  - Ionization: Saha
  - Excitation: Boltzmann
- Radiation temperature <= MC photon flux
- Gas temperature = radiation temperature

t(i)

T(x,y,z)

Ionization (LTE)
X(x,y,z,element,ion)

Saha equation x 92 x 30^3

opacity
τ(x,y,z,wavelength)

b-b transition x 10^6 x 30^3

10^9 photon

Monte Carlo
photon transfer

T(x,y,z)

Ionization (LTE)
X(x,y,z,element,ion)

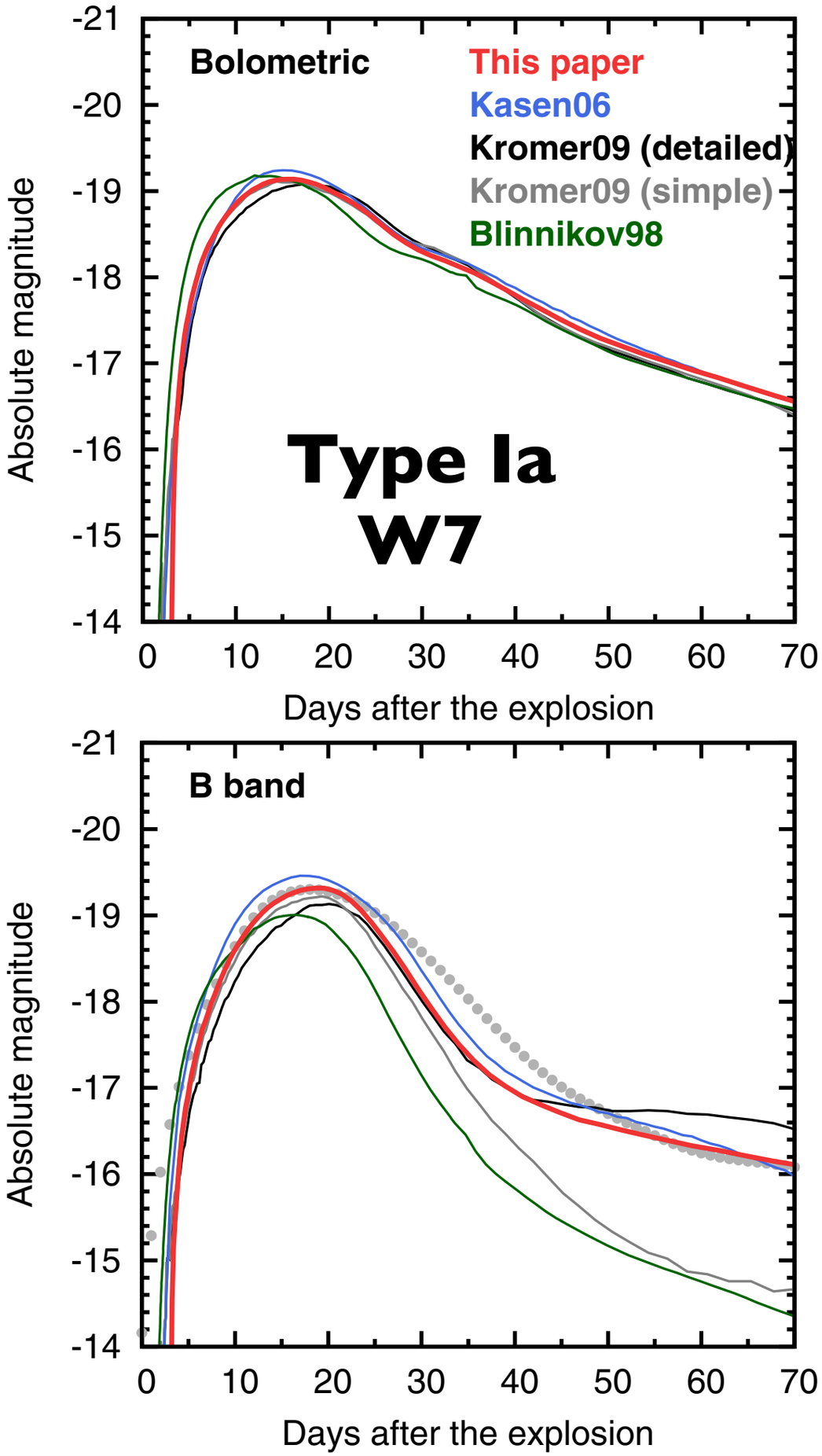
opacity
τ(x,y,z,wavelength)

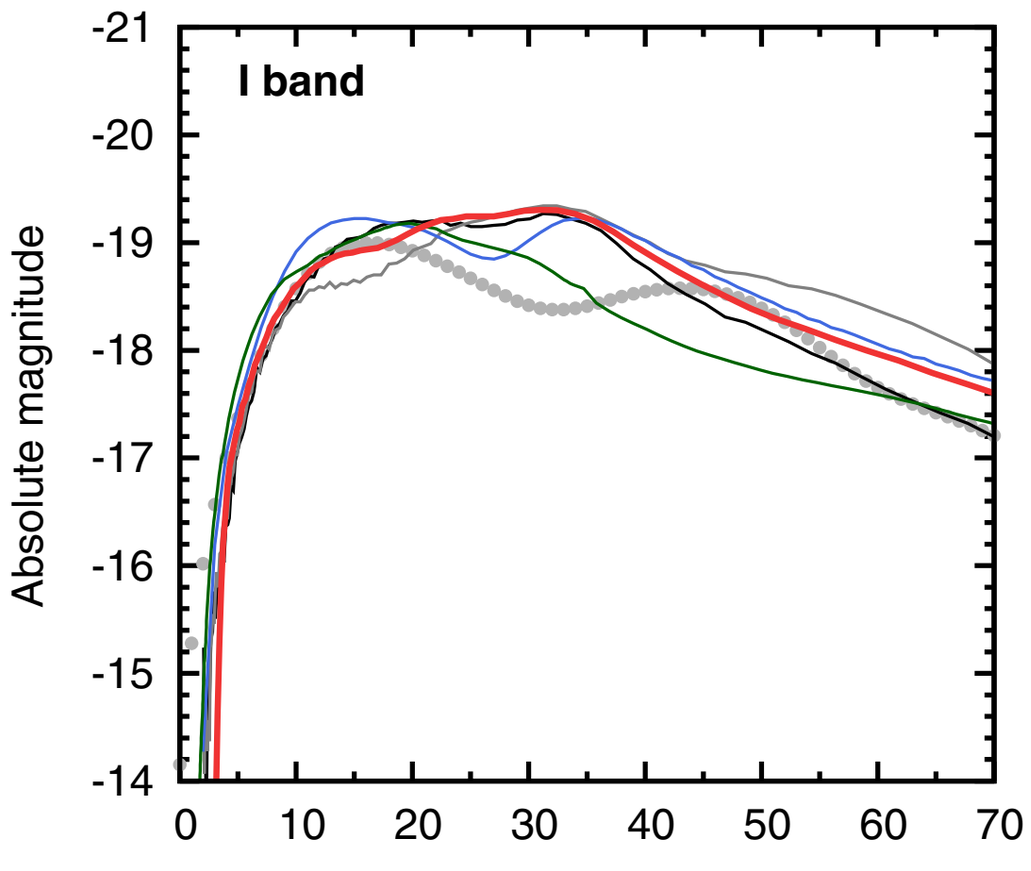
...

t(i+1)

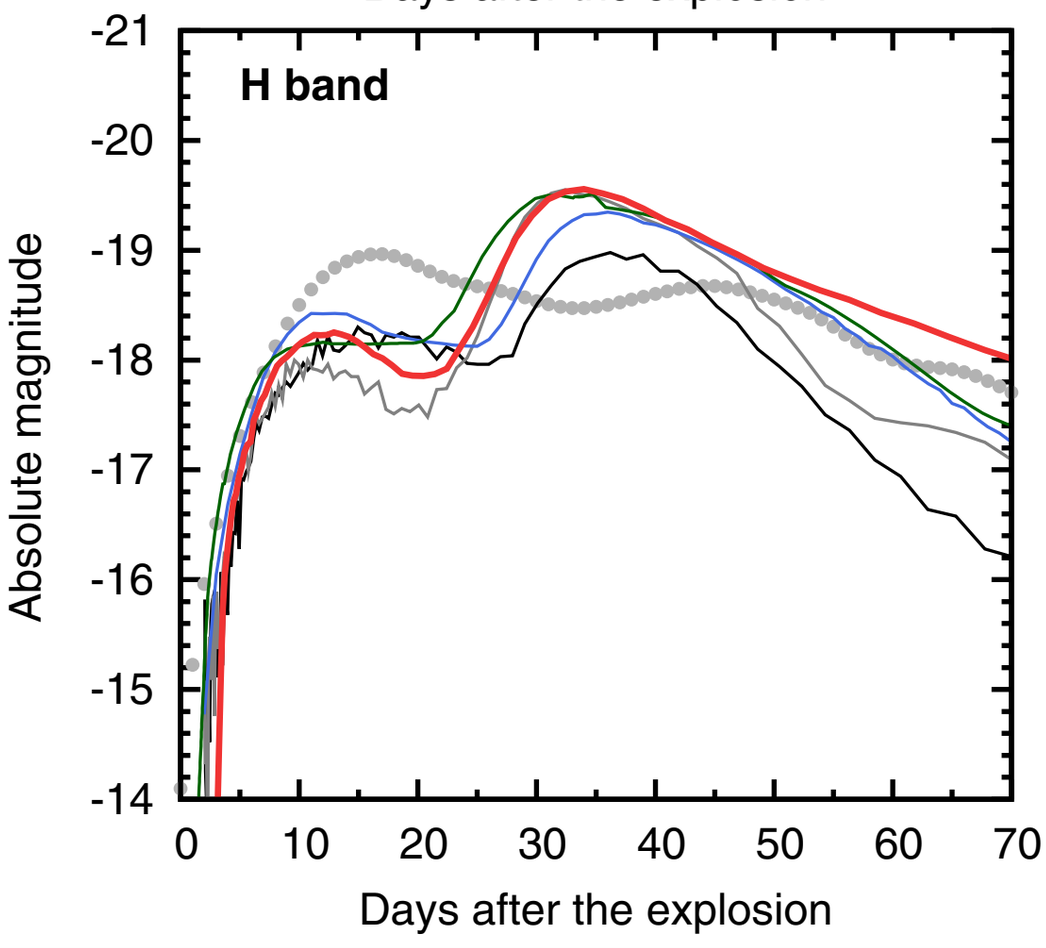
T(x,y,z)

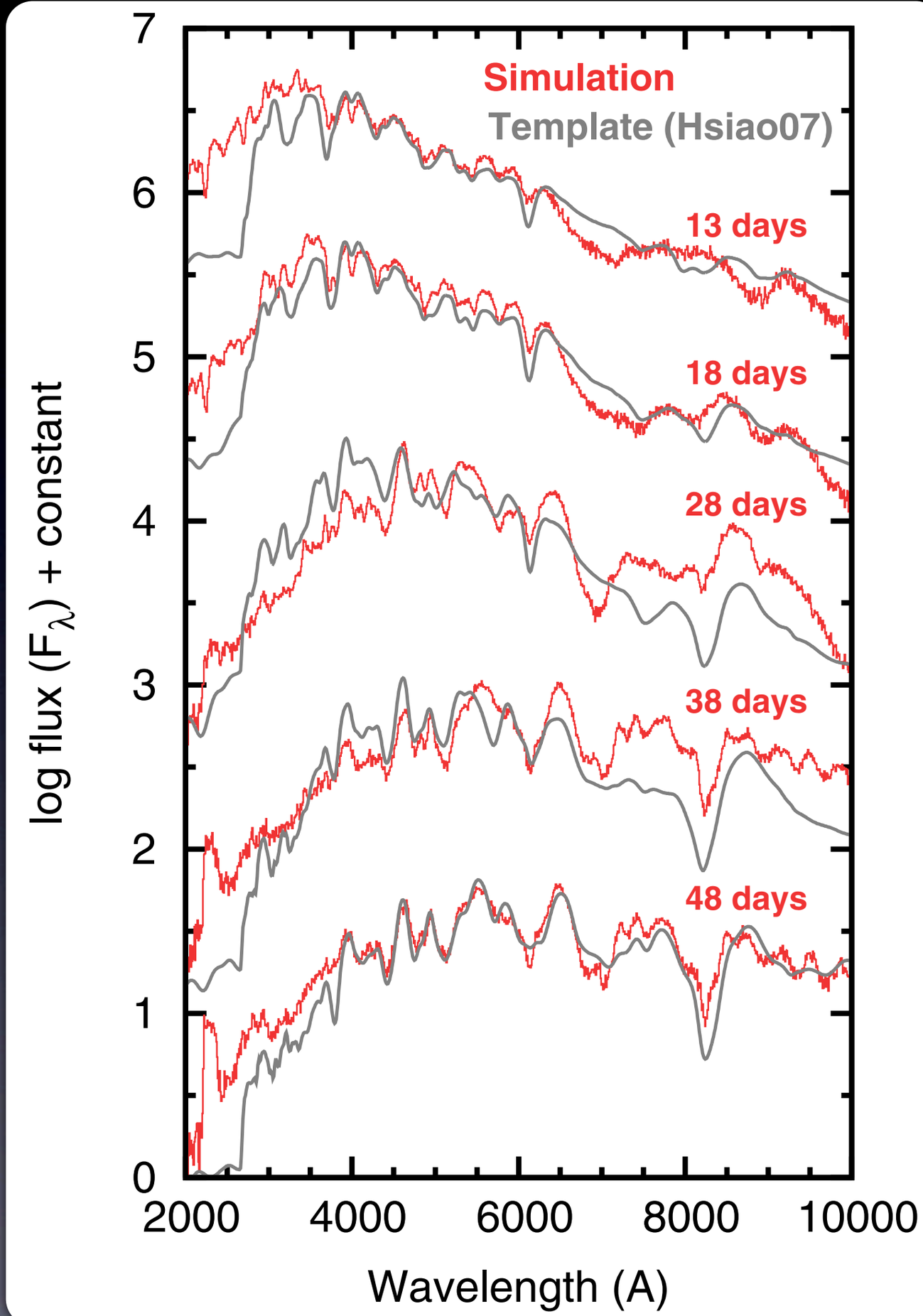
NAOJ Cray XC30
500 TFlops
24,000 cores

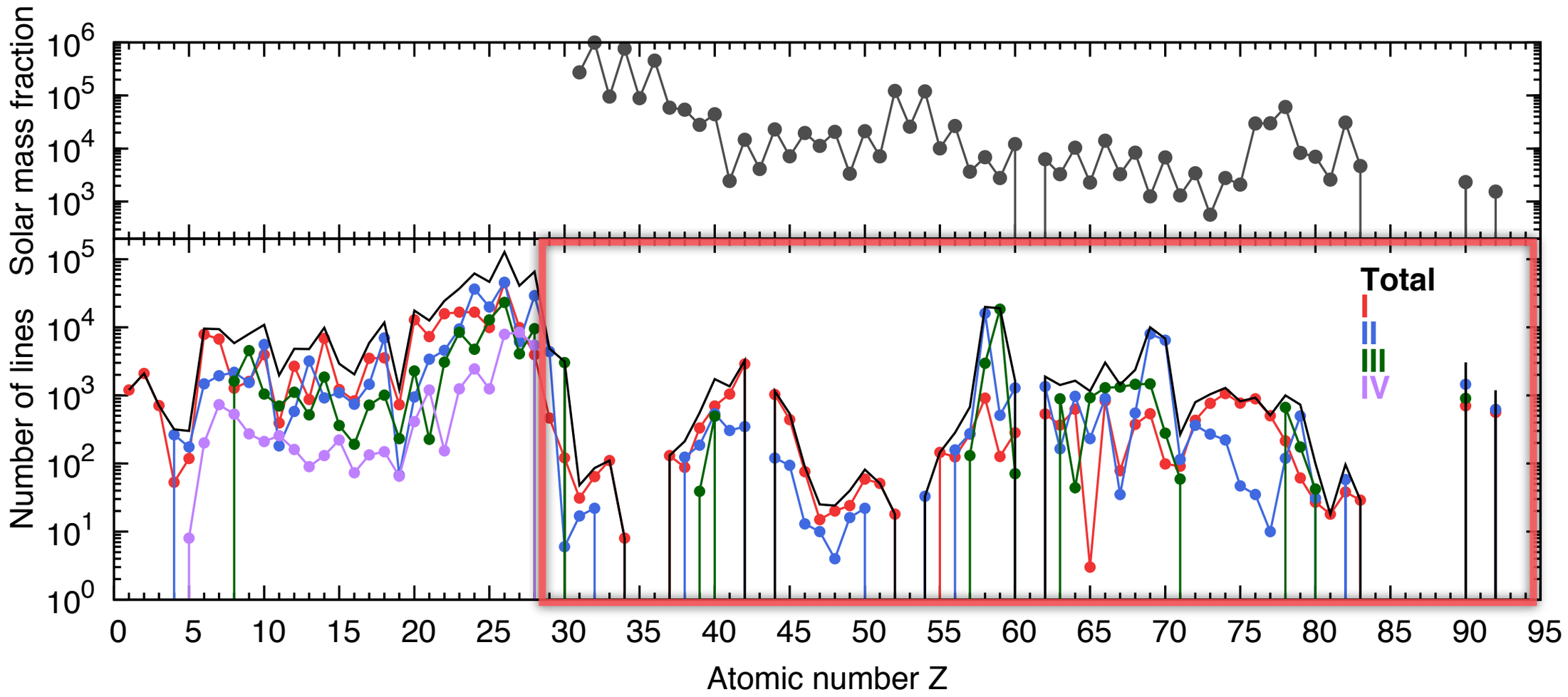

Bolometric
This paper
Kasen06
Kromer09 (detailed)
Kromer09 (simple)
Blinnikov98
Type Ia
W7
Absolute magnitude
Days after the explosion


I band
Absolute magnitude
Days after the explosion

B band
Absolute magnitude
Days after the explosion

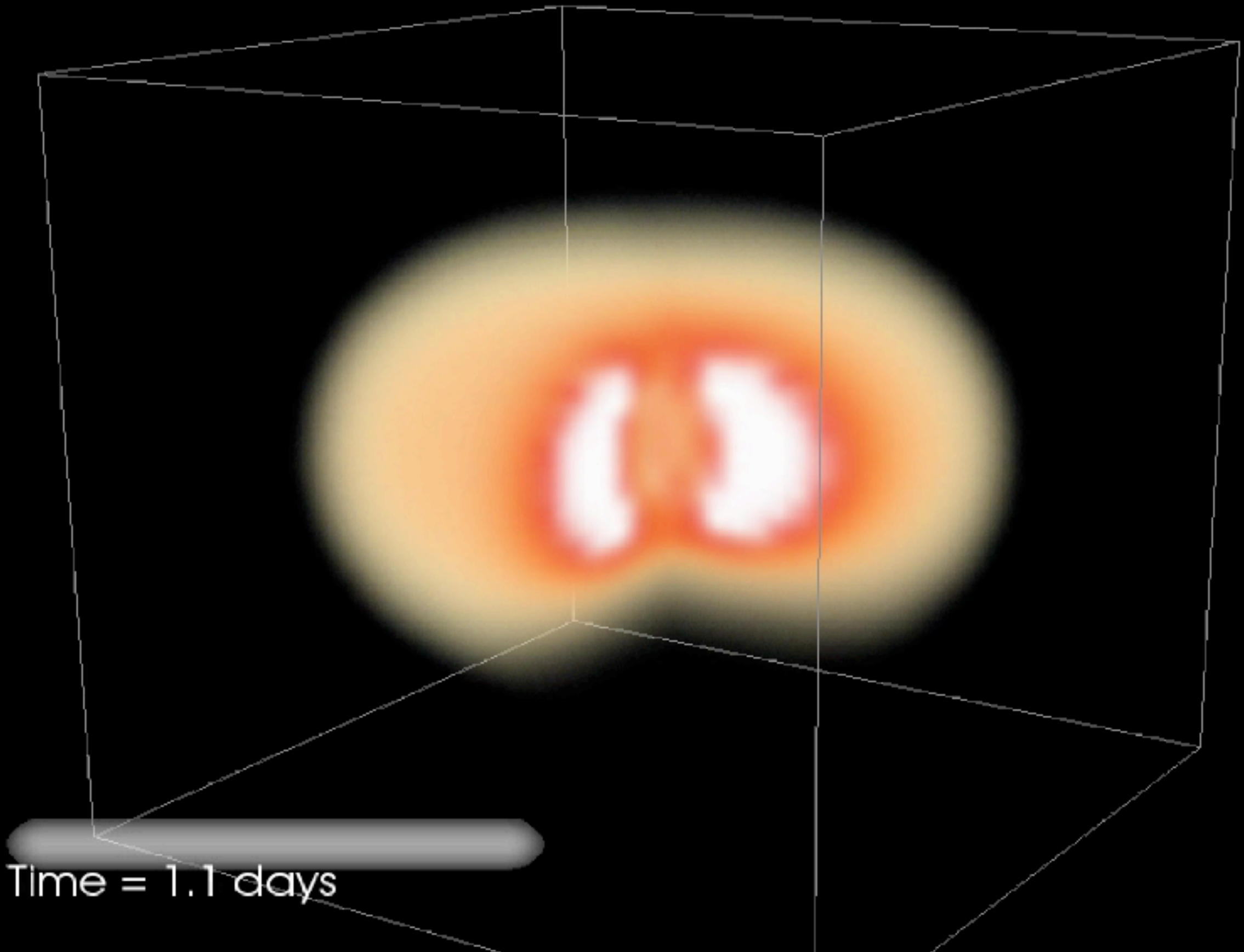

H band
Absolute magnitude
Days after the explosion

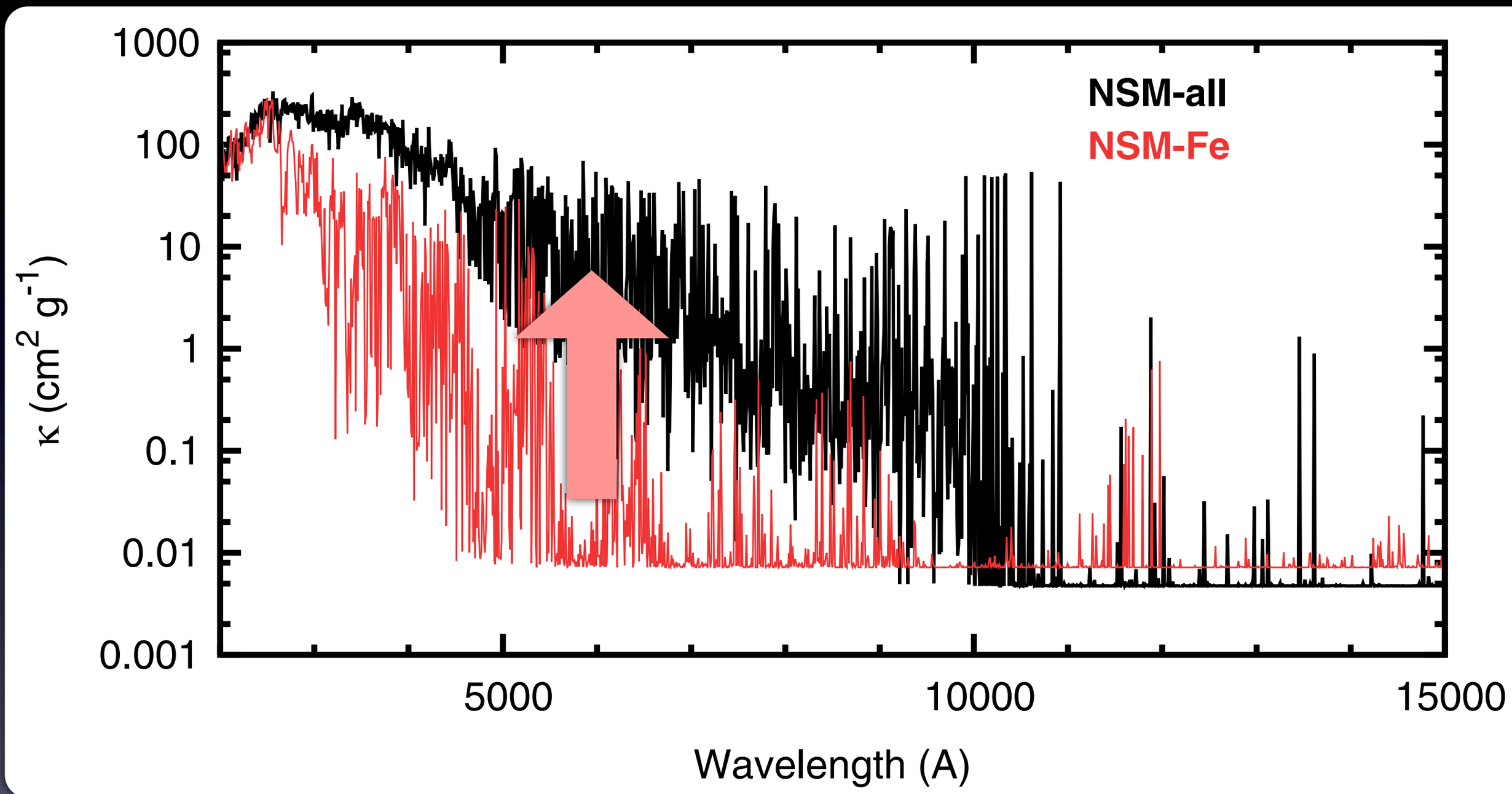

Simulation
Template (Hsiao07)
13 days
18 days
28 days
38 days
48 days
log flux (F_λ) + constant
Wavelength (A)
0
1
2
3
4
5
6
7
2000
4000
6000
8000
10000



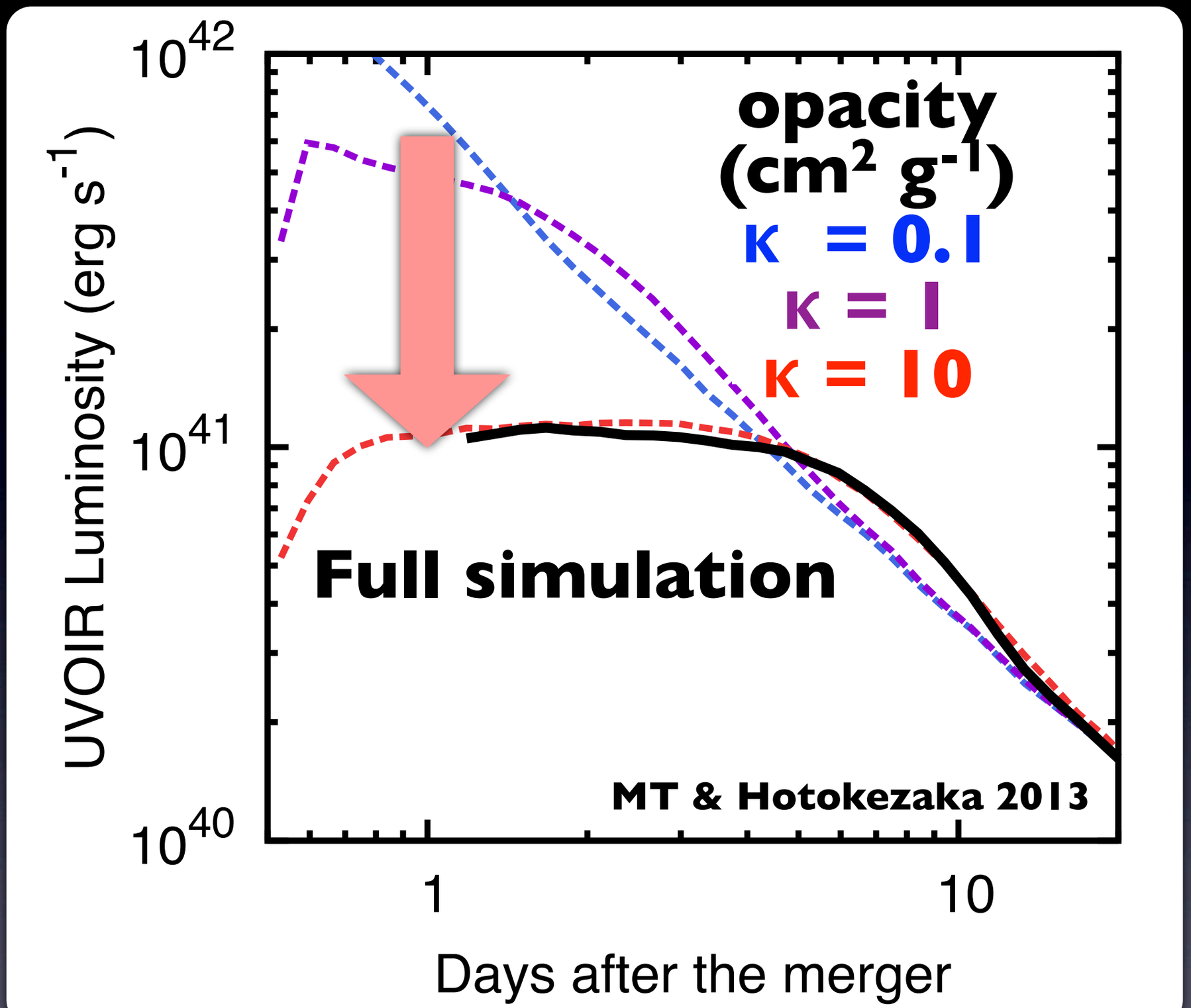
~500,000 transitions (up to Fe)
+100,000 transitions (r-process)

Evaluate bound-bound opacity
(in each time step)


Time = 1.1 days

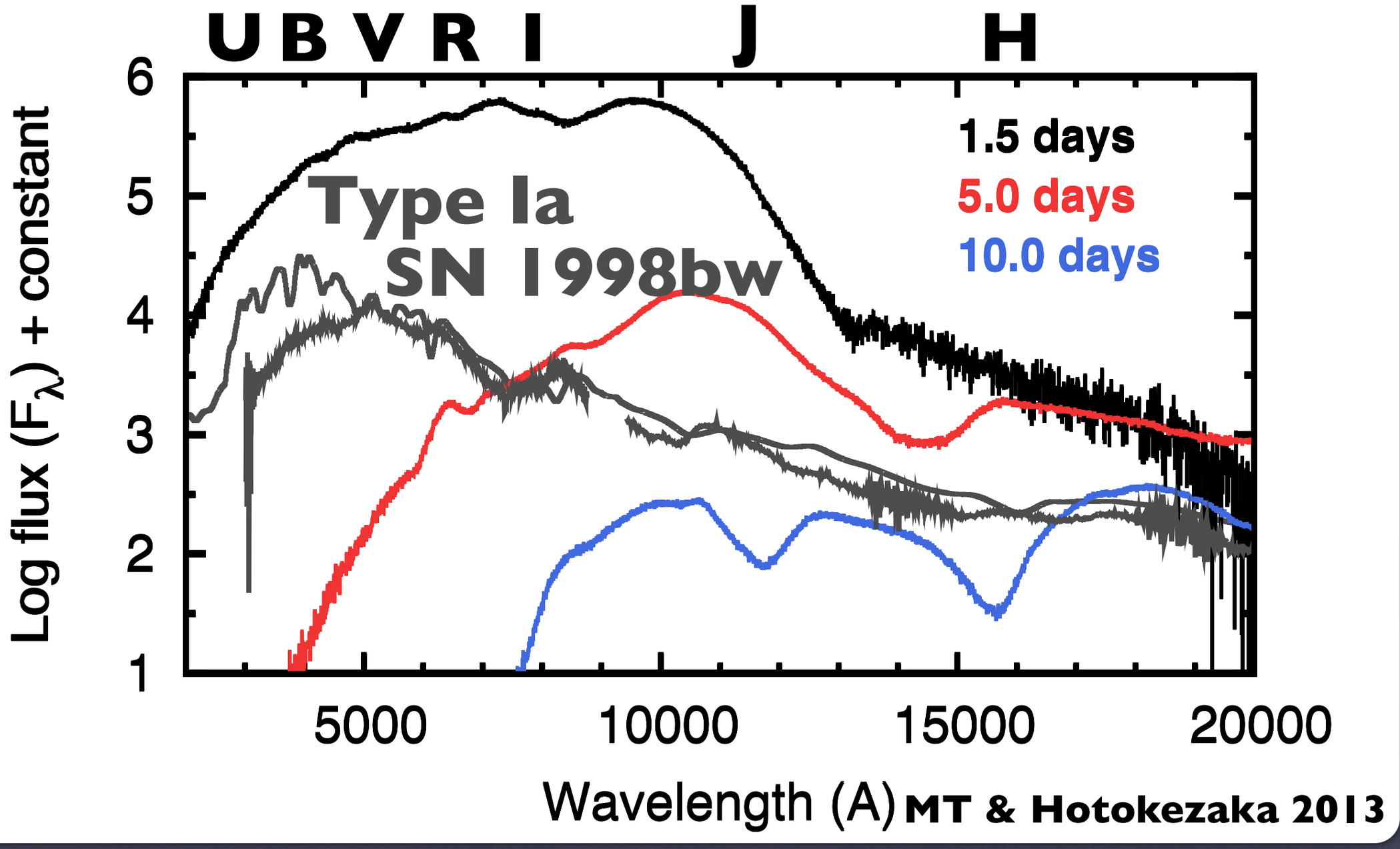


Higher opacity by factor of 100!



Fainter than previously expected by a factor of 10!

(consistent with Kasen+13, Barnes & Kasen 13)



- **Very red SED (peak at NIR)**
- **Extremely broad-line (feature-less) spectra**

(Identification of r-process elements seems difficult)

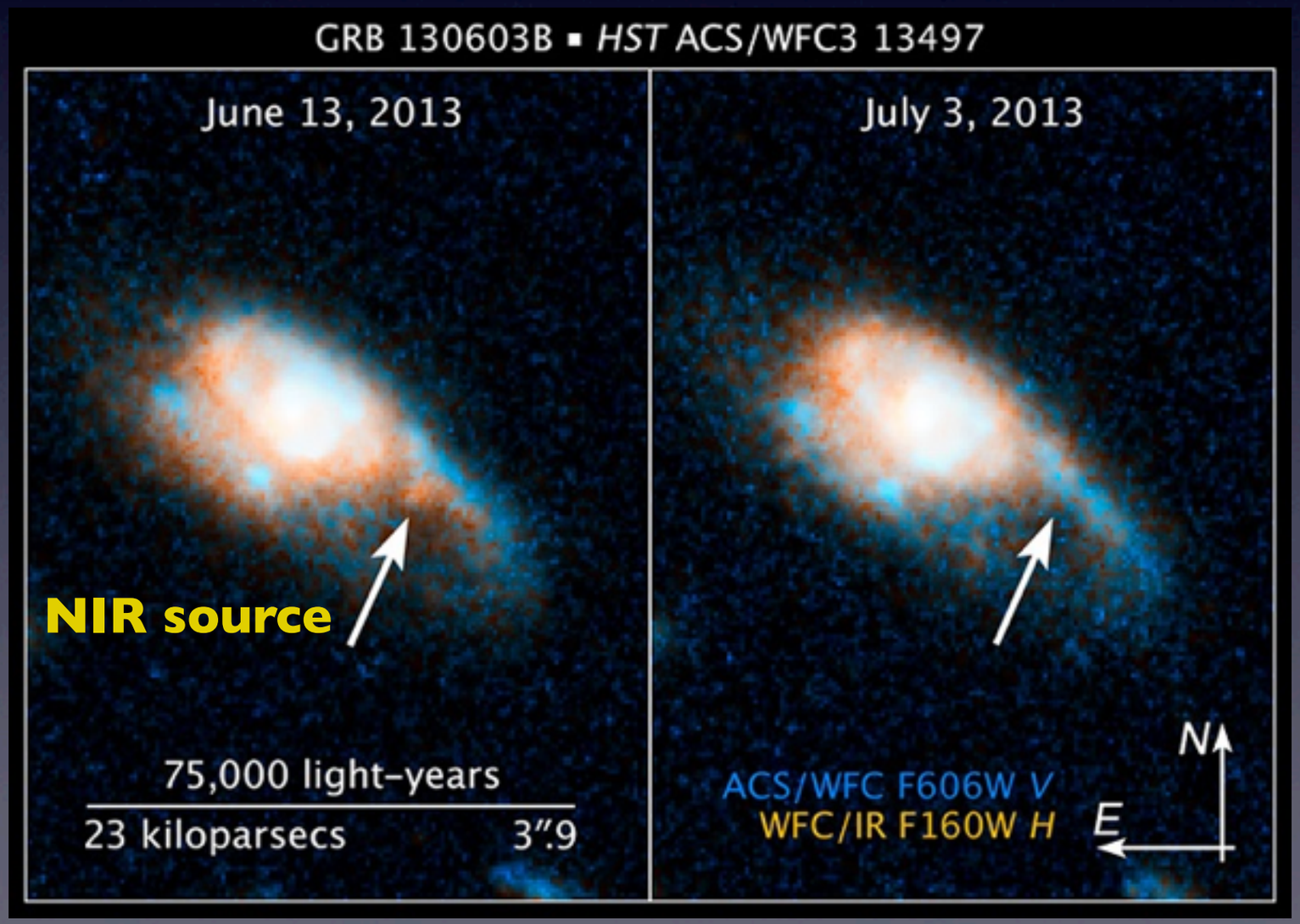
LETTER

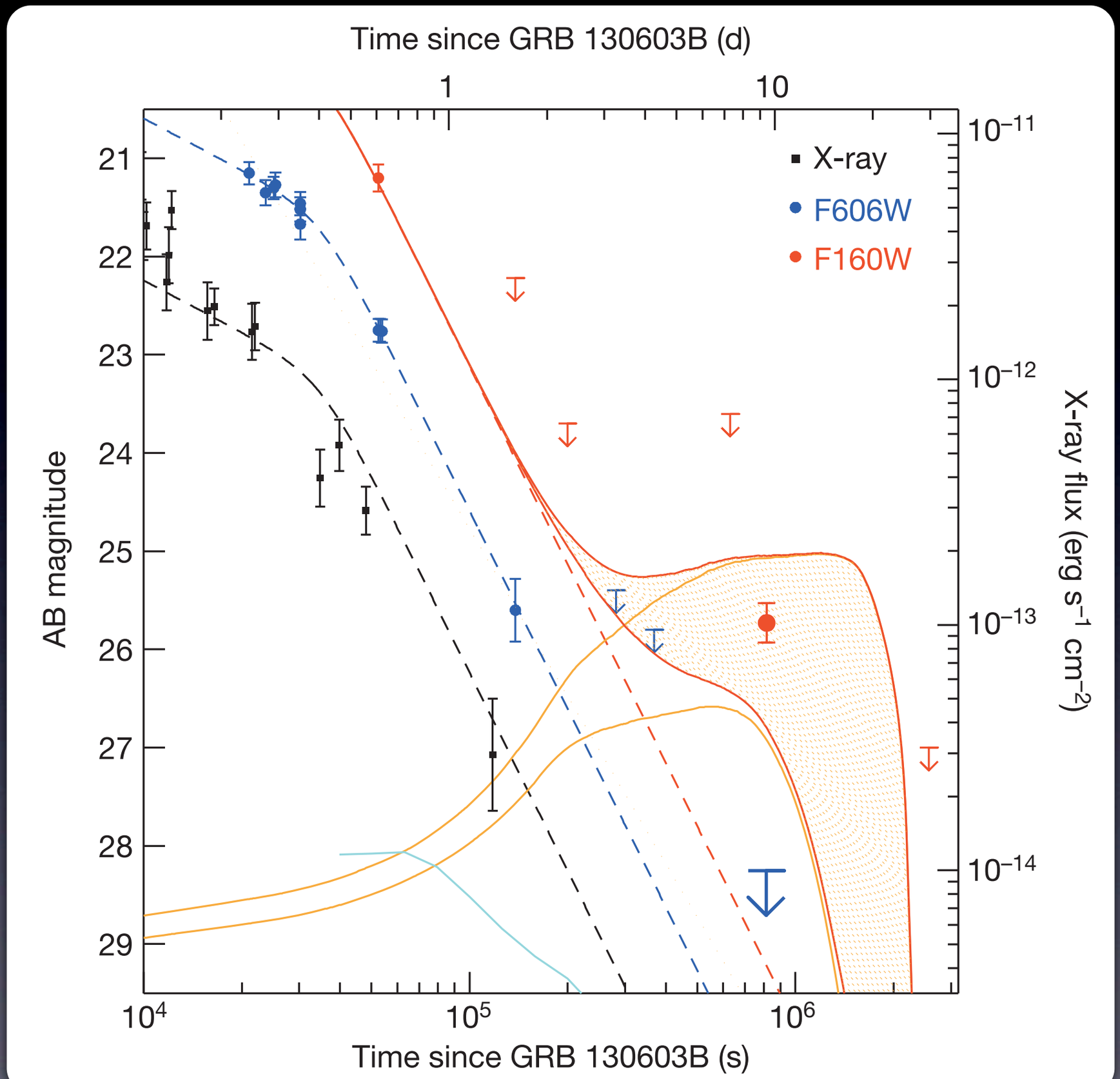
doi:10.1038/nature12505

A 'kilonova' associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. Hjorth[4], R. A. Hounsell[3], K. Wiersema[1] & R. L. Tunnicliffe[2]

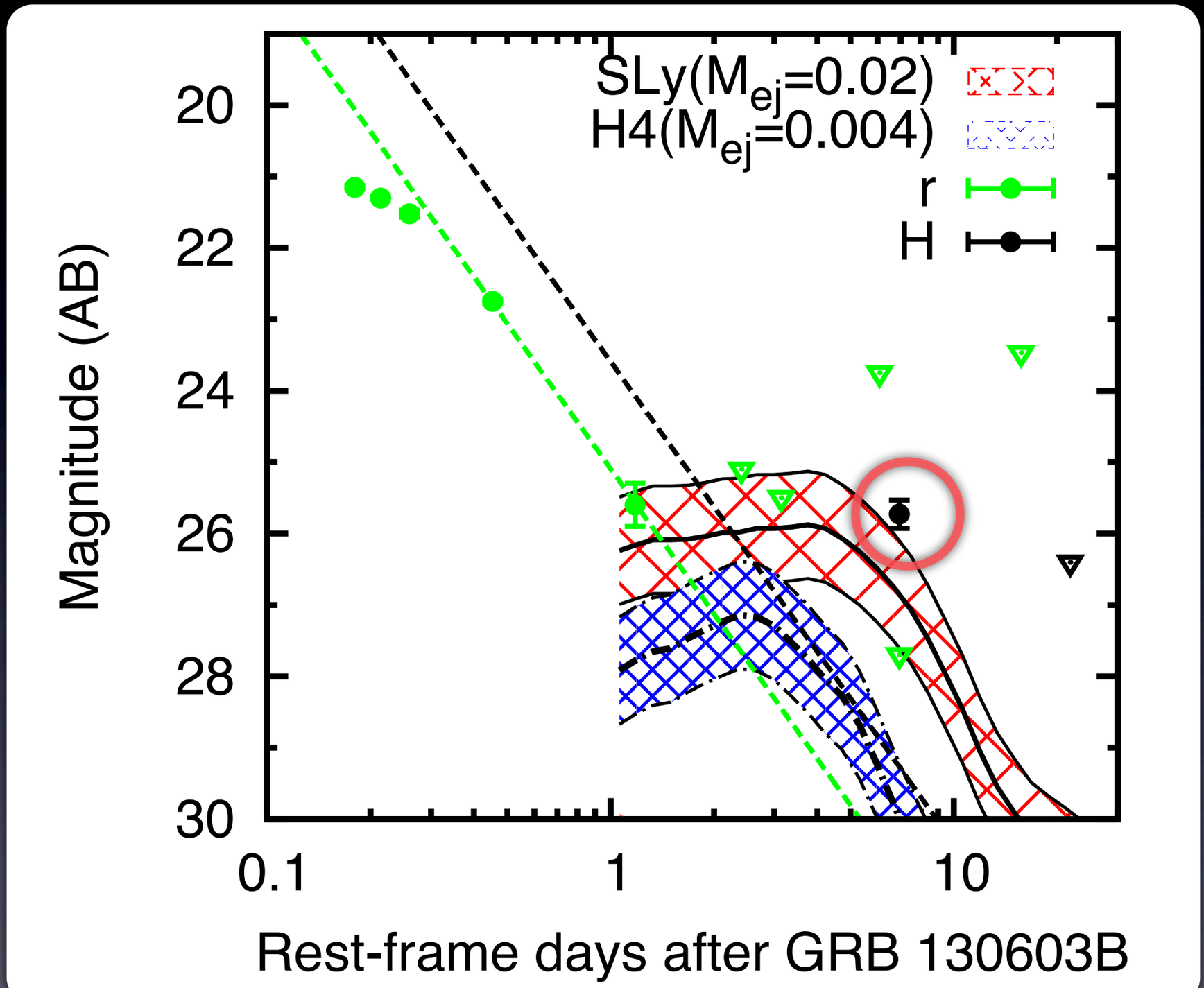
Berger+13
Tanvir+13





Tanvir+13
Berger+13

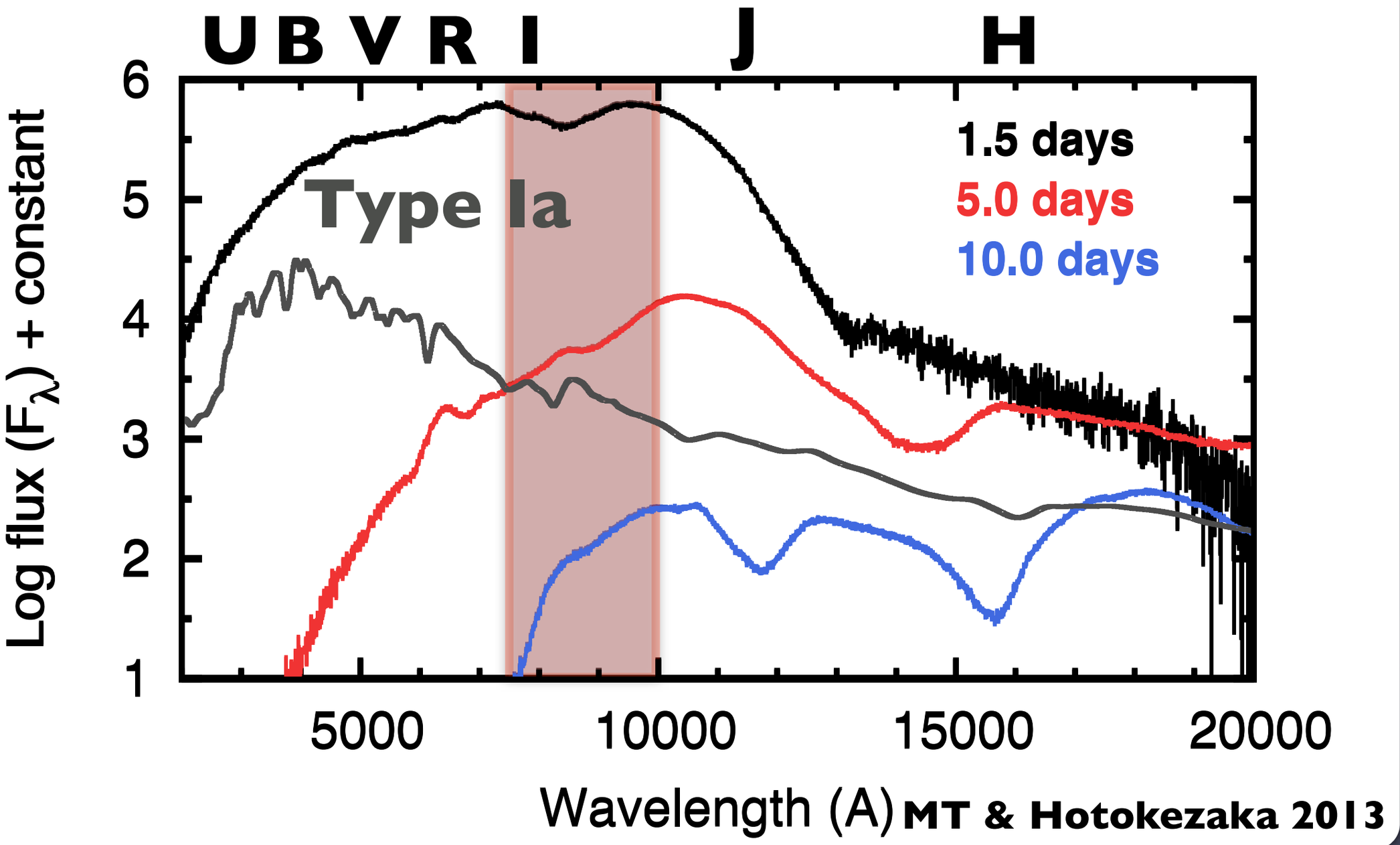
Application to GRB 130603B



Observations by Berger+13 and Tanvir+13

Hotokezaka+13

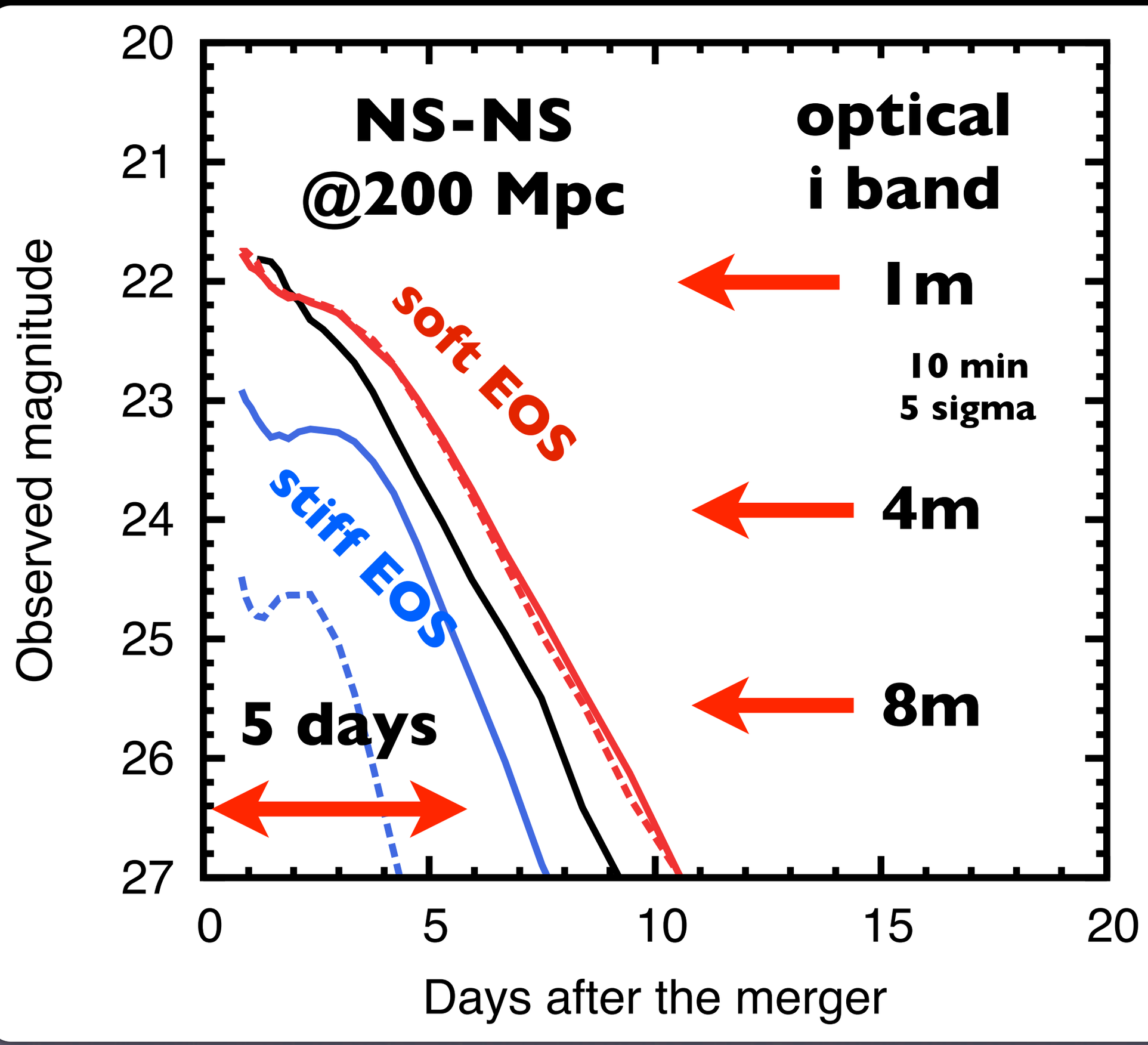
Observing strategy after GW detection

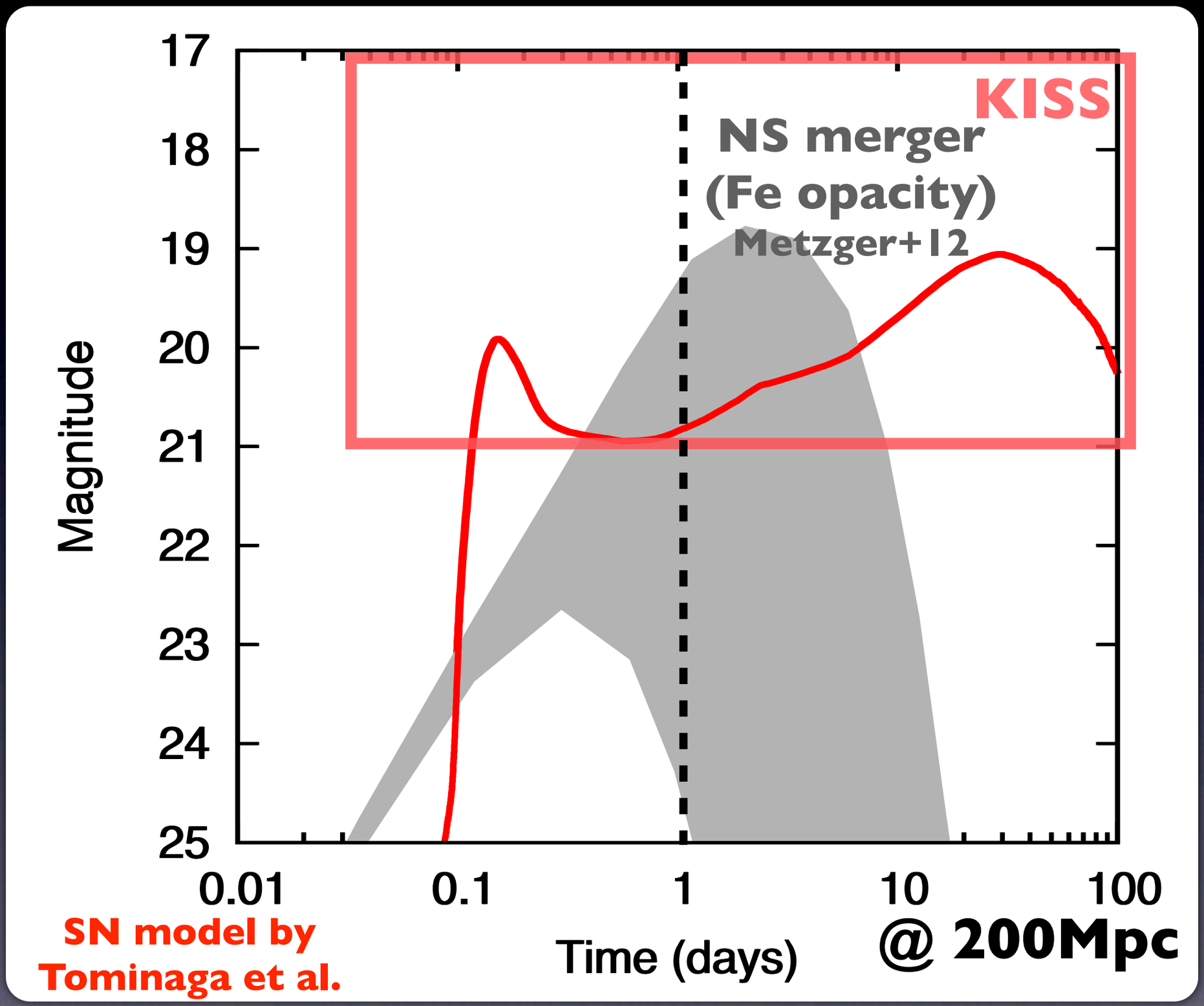


optical

NIR

Best with i/z band (0.8-1.0 um)
(FOV of NIR telescope is small)


NS-NS
@200 Mpc
optical
i band
1m
10 min
5 sigma
4m
8m
soft EOS
stiff EOS
5 days
Observed magnitude
Days after the merger
20
21
22
23
24
25
26
27
0
5
10
15
20


KISS
NS merger
(Fe opacity)
Metzger+12
Magnitude
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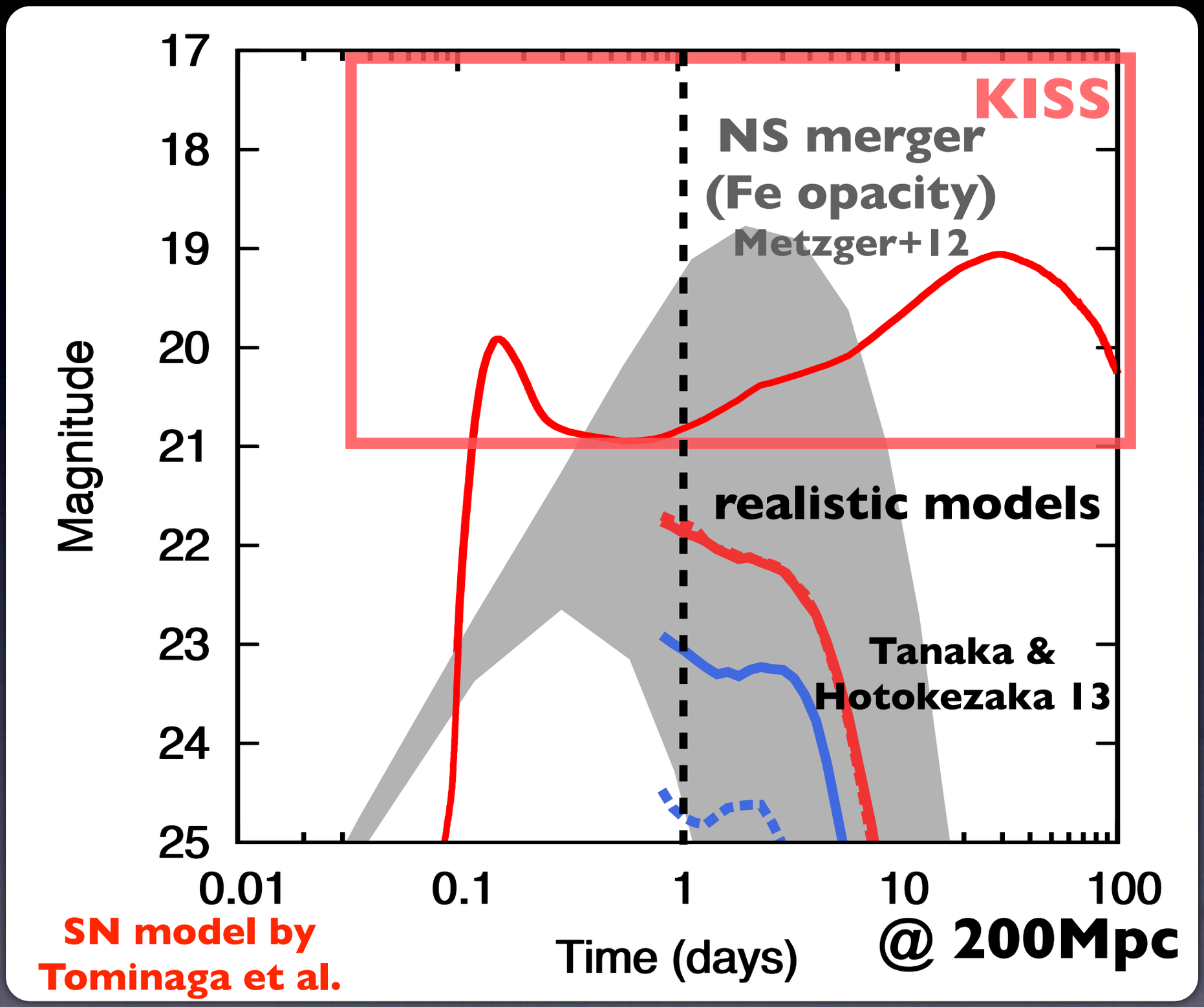
Time (days)
@ 200Mpc
SN model by
Tominaga et al.



4m

8m

1m class telescopes for nearby events

GW alert error box

e.g. 10 deg x 10 deg

~ 5000 galaxies

(< 200 Mpc)

Pan STARRS 1.8m

3.0 deg

PTF 1m

2 deg

8m LSST

3.5 deg

8m Subaru

Hyper Suprime-Cam

1.5 deg

Typical 8-10m telescope

0.3 deg

Transient survey with Subaru/HSC

Hyper Suprime-Cam (HSC)

3m

3t!!

1.75 deg^2

116 CCDs

Data analysis pipeline installed by
Nozomu Tominaga, Hisanori Furusawa,
Naoki Yasuda, Tomoki Morokuma, and MT

Pilot survey with Suprime-Cam (2014 Jan 3-4)

Mauna Kea, Hawaii

Photo by Nozomu Tominaga

Summary

- MC radiative transfer for NS mergers
  - Higher opacity than Fe by a factor of 100
  - SED peak at near-IR
- KISS: high cadence transient survey
  - Shock breakout
  - EM counterpart of GW sources
- Observing strategy
  - 22-25 mag (i band) => 4-8m class telescopes
  - Extremely broad-line spectra